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PRINCIPLES OF METALLURGY OF FERROUS METALS

LEON CAMMEN

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PRINCIPLES OF METALLURGY OF FERROUS METALS.

A MANUAL FOR MECHANICAL ENGINEERS

BY

LEON CAMMEN, M.A.

THIRD EDITION, REVISED AND ENLARGED

NEW YORK
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FOREWORD[1]

MEMBERS of the Society who received their engineering training ten or more years ago will recall that the courses in metallurgy then taught dealt largely with the smelting and refining of metals from their ores. These were considered the special interest of students in mining and were generally taken by few mechanical engineers. The use of the microscope for the examination of metals was confined to laboratory research, and few there were who were competent to draw correct conclusions from microscopic studies.

How engineering practice has changed in a few years! Now one seldom buys condenser tubes without requiring photomicrographs to indicate grain size. Special steel castings and various alloy products are photomicrographed in the course of ordinary production. Welds, bends, and heat-treated sections are examined under the microscope, and accurate deductions can be drawn from such studies. The microscopic study of metals has become a part of our industrial and commercial practice.

Metallography is thus established as a feature of present-day engineering practice. As more knowledge of the art develops, it will be used still more widely. There is every probability that metallographic methods will be quite widely used in the coming years. Engineers will therefore need information on this subject so that they may deal intelligently with problems involving metals and their application.

Busy engineers have little opportunity to study the various able works on this subject. Many of these are quite technical in their treatment and go into greater detail than is necessary for the average engineer. The Publication Committee of this Society believed that a series of articles on the subject of the newer metallurgy written in simple language, would be welcomed by our members. Your editor arranged with an engineer familiar with the subject for the preparation of such a series, and this series is presented in the following chapters.

The subject is not an easy one to treat in a popular manner, for it involves some of the later concepts of matter, some physical chemistry, and many new ideas associated with the heat changes and heat treatment of metals. In fact, specialists are not in complete agreement regarding the nature of many of these phenomena. The author of the articles has endeavored to maintain a judicial atti-

[1] Editorial in *Mechanical Engineering*, May, 1925, referring to the series of articles here reprinted from that journal with certain additions.

tude on such subjects and has presented what seems to him to be the more generally accepted views. During their preparation these articles were reviewed by several engineers familiar with the subject, and their suggestions have been incorporated where possible.

While these articles cannot be expected to make expert metallurgists of our members, it is hoped that they will familiarize each reader with the terminology of the subject and enable him to have a clearer appreciation and a better understanding of the preparation, use, and interpretation of photomicrographs with which he may have to deal in his professional endeavors.

ALEXANDER GRAHAM CHRISTIE.

PREFACE TO THE THIRD EDITION

PART of the material published in this book was originally printed as a series of articles in *Mechanical Engineering*, beginning with May, 1925. These articles were reprinted with considerable additions in book form in 1926, and again in 1927. The first and second editions have been exhausted, and in preparing the present edition some revision of the original material has been made in order to bring it up to date.

Two new chapters, one on Forging and the other on Casting (steel and gray iron), have been added. Like the rest of the book, these two chapters have been written primarily not for makers of castings and forgings but for those who have to use them: for example, mechanical engineers who specify cast or forged parts in their designs.

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PRINCIPLES OF METALLURGY OF FERROUS METALS

CHAPTER I

PHYSICO-CHEMICAL PROPERTIES OF IRON ALLOYS

Introductory

A piece of steel in many respects resembles one who examines it. Like him it has properties which are determined by the materials of which it is composed, by the treatment it has received—its life history, by forces that act invisibly within it, and finally, by its environment. It will be the purpose of this book to discuss briefly all of those influences which contribute to make a piece of steel what it is, to the satisfaction or dissatisfaction of its users.

Every commercial iron alloy is essentially the product of an alliance, mechanical or chemical, between the primary elements iron and carbon, affected as it always is by the presence of what may be called subsidiary or incidental constituents such as manganese, silicon, sulphur, phosphorus, oxygen, nitrogen, and hydrogen. Special iron alloys have also such elements present as nickel, chromium, copper, cobalt, tungsten, molybdenum, etc. singly or in combinations of two or more. Finally there are elements which first appear in and then disappear from the iron alloy at some stage or other of its manufacture, producing beneficial or harmful results by virtue of some reaction which they have been instrumental in accomplishing. Metals like titanium and, to a certain extent, vanadium and such so-called deoxidizers as boron, aluminum, and magnesium may materially affect the character of a steel without being actually present in the final product, through the fact of their having introduced or eliminated undesirable constituents or exercised a more or less permanent effect on the structure of the metal. What is not always realized is that a very large proportion of the carbon used in the manufacture of steel acts in exactly this way.

In the first place, therefore, the character of a steel, or in fact, of all iron alloys, is determined by the materials that go into its making. It is also affected by the way in which the steel is made. The method of melting and, in particular, the ability to control the various steps in the process, and hence the final product, is one of the factors the importance of which has not been fully realized. The whole difference between bessemer steel on the one hand and open-hearth steel on the other, depends on this very fact. The excellence of many grades of electric steel is likewise probably due to the ability to control the product more than to any other factor.

The amount of gases dissolved in the steel, which affects the soundness of the ingot, is also a factor which may or may not be controllable during its manufacture, with the result that the strength of the ultimate product may be favorably or unfavorably affected by the degree of controllability exercised and by the knowledge of the extent to which dissolved gases should be permitted to remain in the steel at the time of its teeming.

Finally, the handling of the molten steel, a subject about which very little indeed is to be found in books, affects the character of the metal to a far greater extent than is generally realized. When steel is teemed from a furnace into a huge ladle and the ladle is set aside for, say, twenty minutes to permit the metal to settle, something is done which is of truly vital importance in determining the character of the final product, yet one may look in vain through metallurgical literature to find strict justification for this apparent waste of time.[5]

The temperature at which the metal is poured into an ingot mold, the rapidity with which the latter is stripped and the ingot transferred to the soaking pit, the design of the ingot mold, the use or failure to use hot tops, the shape of the ingot, are all important items in the process of manufacture that determine each in its own way the properties of the final product.

As a matter of fact, from the moment the molten steel reaches the walls of the mold there are a series of processes at work in shaping its quality and characteristic properties which do not cease until the final operation on the product. The rapidity of freezing and cooling of the steel, its ability to hold dissolved gases, the thermal and chemical processes which produce what is known as segregation of the non-metallic elements, the strains in the ingot, the development of planes of weakness induced by these processes, and the character of crystallization of the steel are but some of the factors which determine the properties of the material in the ingot. The ingot is not, however, the final product except in the case of castings, and in all other cases it is but a starting point for other operations.

These operations, which comprise various kinds of forging, rolling, drawing, pressing, and spinning, introduce numerous other influences which modify favorably or unfavorably the characteristics already present in the ingot, and these in their turn may be followed by a new group of operations such as machining, stamping, grinding, etc. at times capable of still further modifying the properties of the metal.

And then there is heat treatment, which, like the fiery bath of the fairy tale, permits steel to purify itself of most of its sins of improper crystallization, and, one might say, to start life anew, with a clean slate, and build up a structure that may be tough or brittle, hard or soft, practically as desired.

When, therefore, we look at a piece of steel we can envisage it

in a way as a distinct personality with a long past history. We know that the character of a man is affected by the race from which he sprang, in other words, by those physical and mental ingredients which went into his original make-up. It is also affected by the conditions under which the most impressionable periods of his life—childhood and youth—were passed, by the schooling he received, and by the environmental influences that were brought to bear upon him. The same is essentially true of steel. The metallurgist has to know all of those influences which affect the ultimate character of steel just as an expert diagnostician has to understand similar influences in the case of a man. It is not an easy task because of the very great complexity of the factors affecting and determining the characteristic properties of steel, only a part of which have been enumerated above. There are, however, certain basic underlying processes and physical and chemical laws which lie at the foundation of all the vital processes governing the making, shaping, and treating of the master material of the world—steel. In the present book an effort will be made to discuss somewhat briefly, and, as far as possible, in non-technical language, these basic underlying physical and chemical processes rather than the actual manufacture of steel through all its maze of complexities.

Composition of Iron Alloys

In dealing with ferrous metals, or alloys of iron such as cast iron, steel, and wrought iron, the mechanical engineer is primarily interested in knowing whether and why a certain piece of metal is tough or brittle, strong or weak, capable or incapable of withstanding vibration and repeated shocks, and whether or not it can be improved by proper treatment. Essentially, it is not the problem of the *mechanical* engineer to produce the kind of steel or cast iron which would answer his purpose. This is primarily the business of the metallurgical engineer, but it is important that the mechanical engineer should understand clearly what makes a certain material suitable or unsuitable for his purposes and what fundamental properties a material should possess to be suitable for the use to which he proposes to apply it. This is highly desirable because it will help him in preparing specifications for the material that he will use or to act intelligently in selecting the proper material for his purposes. Assume, for example, that a mechanical engineer is designing a boiler for a pressure of 600 lb. and a superheat of 600 deg. fahr. Here ultimately the material of the boiler is subjected to two influences: the mechanical influence of the pressure, which is comparatively easy to calculate by employing certain formulas; and the influence of the temperature of the steam, which may greatly modify the ability of the metal to withstand the mechanical stresses. Now, if an engineer were entirely ignorant of the fact that at temperatures in excess of 1000

deg. fahr. pronounced weakening occurs in ordinary steel, he might specify a material that would merely withstand certain mechanical stresses without calling the attention of the metallurgical engineer to the fact that unusually high temperatures were to be dealt with, and this would unquestionably result in the failure of the steel recommended. This is a rather crude example, but it will serve to show how important it is for the mechanical engineer to have a clear conception of the various influences affecting metals in order to be capable of dealing intelligently with the problem of selection of materials for his special purposes.

All ferrous materials (which term includes cast iron, malleable iron, white iron, carbon and alloy steels, and wrought iron) are essentially combinations of the element iron (Fe) and the element carbon (C). All commercial ferrous materials contain small or large additions of other substances, some of which are merely impurities derived from the ores, fuels, or fluxes and cannot be entirely removed in the process used for commercial manufacture. Of these the most important are sulphur and phosphorus. Other elements may either be inherited by the metal from its ores or be deliberately introduced into it during the process of manufacture for the purpose of counteracting the harmful properties of impurities or conferring on the metal certain desirable properties. Among these may be mentioned manganese, silicon, chromium, nickel, vanadium, cobalt, etc. There are finally certain materials which are introduced into the metal during its process of manufacture in such a manner and in such quantities as to produce certain results and then be more or less completely eliminated. Such are, for example, aluminum, magnesium, cerium, uranium, and titanium. Of these more will be said later. Our primary interest lies in the compounds involving carbon and iron, it being, however, clearly understood that the formation, character, and stability of these compounds may be affected by the presence of the other elements above referred to. Because of this we shall at first deal with ferrous materials where the amount and character of the impurities are such as not to affect to any considerable extent the iron-carbon compounds.

Factors Affecting the Structure of Iron Alloys

The character of the iron-carbon compounds in all ferrous materials depends on three factors which we shall consider in succession. The first of these is the ratio of the carbon content to the iron content. The second is the effect of the processes which take place during the passage of the ferrous material from the liquid state to the solid state, the exact meaning of the terms "liquid state" and "solid state" being more fully explained later. The third is the mechanical, thermal, and chemical treatment of the material after it has reached its solid state.

As regards the chemical constitution of iron-carbon compounds,

it is important to understand that as far as we know only one such compound can be formed and that is the carbide of iron, the chemical formula for which is Fe_3C. This compound consists of 6.6 per cent carbon and 93.4 per cent iron and is usually called "cementite." It would appear, furthermore, that in some way or other only a certain proportion of the iron will under our present conditions of manufacture take up the carbon necessary to produce cementite, no matter how much carbon may be actually present, the remainder of the iron retaining its freedom. In this way, and as a result of the interaction of such agencies as heat, solid solution, etc. a series of iron-carbon compounds are produced which, with essentially the same chemical composition, exhibit different characteristics. These compounds have been given special names, such as austenite, martensite, troostite, hardenite, sorbite, pearlite, etc. The exact meaning of these terms and the properties of the bodies thus denoted will become clear in the course of this book. These bodies may pass from one into another when subjected to certain influences, especially heat.

If the structure of an iron alloy depended merely on its chemical composition, cementite and iron in their various combinations would explain it entirely. As a matter of fact, however, there are other factors besides chemical composition which must be taken into consideration. The first is that iron may occur in at least three forms, depending on the heat treatment to which it has been subjected. This happens with a good many materials such as sulphur and phosphorus and is called "allotropy."* More will be told about it in the chapter on The Crystalline Structure of Steel.

The next factor affecting the structure of iron alloys is that the combination of cementite and iron may take a number of forms, even when the content of carbon in the total mass remains constant. This is again a condition very commonly encountered in chemistry, certain materials being stable at one temperature and decomposing or passing into other combinations at other temperatures. A very interesting instance of this has been utilized in the Mond process of making metallic nickel. A compound of nickel and carbon called

* There is no universally accepted definition of allotropy. Professor Sauveur defines it as "suggesting marked and sudden changes in some of the properties of a substance occurring at certain critical temperatures, without any change of state or of chemical composition." Jeffries and Archer (p. 61) define an allotropic change as a change in atomic arrangement, and add that this definition should furnish a positive criterion of allotropy hindered only by the experimental difficulties involved in determining atomic arrangements at high temperatures. A. Smits (The Theory of Allotropy, Longmans, Green & Co., London, 1922, pp. 218–219 and p. 376) discusses the difference between the change from alpha to beta and the change from beta to gamma, and vice versa, from the point of view of retardation of transformation, without giving a general definition of allotropy. While doubting the existence of beta iron as a separate phase, he does not consider the question as settled.

"nickel-carbonyl" is formed at a certain range of temperature, 122 to 176 deg. fahr. It remains stable between these temperatures, but at about 392 deg. fahr., it decomposes into nickel and carbon monoxide, this reaction being used for obtaining a very pure form of nickel. Now iron, which as has been previously stated occurs in three forms, and cementite likewise form several combinations depending on the temperature at which the material is maintained and—what complicates matters still more—the rate of cooling from the molten state, or especially from some of the higher temperatures. In order to understand what happens to a piece of steel we have, therefore, to consider all of these factors.

With very few exceptions, all ferrous products used in engineering are made from molten iron or steel, and passage through the various temperature ranges from that of molten metal to practically room temperature determines their structure and to a very considerable extent their mechanical properties. For purposes of simplicity and completeness it may be well to consider first what happens to a pure metal like iron or copper when it passes through these various ranges.

Assume that we have molten iron (pure) at a temperature several hundred degrees above its freezing point and that the supply of heat to the molten metal has been cut off. The metal will then gradually lose its heat, this loss proceeding under ordinary conditions at a practically uniform rate until the temperature is reached at which solidification begins to set in. It is known that solidification consists in a rearrangement of the molecules, which at the instant of solidification lose the amount of energy that enables them to move about freely. This loss of energy is expressed in an evolution of heat, which stops for a while the further loss of temperature. As the heat evolved by the solidification of the first batch of metal is lost by conduction, convection, and radiation, the loss of a further amount of heat from the metal leads to the solidification of another part of the liquid bath, and this proceeds until the entire liquid has solidified, at which time the whole mass is supposed to be at the same temperature, which is the temperature of solidification for the given metal. It is important to note that when solidification proceeds in the manner described, i.e., gradually, the mass from the time at which solidification commences to the instant at which it is completed consists of a mixture of metal partly liquid and partly solid. It is, however, possible, in particular with liquids freezing at comparatively low temperatures such as water, to cool the liquid several degrees below the point of solidification, provided it is maintained in a state of rest. But if the liquid is then jarred, it will solidify practically instantly. This does not usually happen with iron, so that the first-described process may be considered as fairly standard (for pure iron).

Ferrous materials such as gray cast iron, carbon steel, and alloy steel are, however, not pure metals but compounds consisting of

more than one element, and the freezing of such compounds proceeds in a manner somewhat different from that for pure metals. It also depends to a large extent on whether the compounds of the metal form a solid solution in each other or not. We may consider first the case when no solid solution is formed, i.e., when the constituents separate completely on freezing. Assume that the molten bath consists of a metal of high melting point H and a metal of low melting point L. It is further assumed that H is preponderant in the mixture. As the bath reaches the temperature at which H, when present in the mixture, begins to solidify, a small amount of it will freeze, and it is important to bear in mind that the melting point, or conversely the freezing point, of H when present in a mixture of metals such as H and L, is lower than that of H alone, decreasing with an increasing content of L up to a certain point. The freezing of even a small proportion of H will leave a bath containing a larger proportion of L with respect to H, and this, in accordance with what has just been stated, will tend to reduce the temperature at which the next batch of H will freeze. This process goes on until the temperature has reached a certain definite limit for the given alloy, at which time the residual bath containing both H and L will freeze without further separation of H out of the bath.

The essential difference between the freezing of the pure metal described previously and the freezing of the mixture described here is therefore that in the case of a pure metal the entire mass freezes at the same temperature though not at the same time, the temperature being maintained constant automatically by the interplay between the natural cooling of the metal on the one hand and the evolution of heat as a result of gradual solidification of the metal on the other. In the case of the mixture of the two metals here described, solidification proceeds over a whole range of temperature beginning with the temperature of solidification of H and ending with the temperature of solidification of what might be called a saturated (with respect to L) mixture of the two metals.

As has been shown above, the gradual freezing out of H continues until the liquid represents a mixture of H and L such as contains a definite proportion of these two elements. Then the mixture freezes as such without further separating out of H. Such a mixture is called a "eutectic" mixture, which means a mixture which is the most fusible or having the lowest freezing point that can be made out of the two given materials.

If, on the other hand, the content of L metal while lower than the content of H metal is still higher than the eutectic percentage, it is metal L that freezes out until the eutectic composition is reached, the stages being the same as in the case of freezing of H metal up to the time when the same eutectic composition is established in the liquid metal. Hence, if the metal is hypoeutectic (less than the eutectic ratio of L) it will ultimately consist of H metal crystals

incorporated in a matrix representing frozen eutectic. If the metal is eutectic to start with, it will freeze uniformly and be of uniform eutectic composition when frozen. If the metal is hypereutectic (L more than eutectic ratio) it will ultimately consist of L metal crystals (as a matter of fact, L does not have to be a metal but may be a metalloid) incorporated in a matrix consisting of a frozen eutectic H and L mixture.

In metallurgy such processes are often represented by means of diagrams, and Fig. 1, which (through the courtesy of D. Van Nostrand Company, New York City) is based on one in Dr. Walter Rosenhain's book, An Introduction to the Study of Physical Metallurgy, page 91, is an ideal equilibrium diagram of a system of two metals which has a eutectic temperature but does not form a solid solution. The line AEB represents the lower boundary of that region in which the alloys are completely liquid and is called by the Latin name "liquidus," the abscissas of the curve referring to the proportions of the metals in the alloy. The line CED represents the upper boundary of temperatures at which the alloy is completely solid. In the case of a simple system of two metals such as is described here, CED is a straight line and extends from XA to ZB. In more complicated systems it may be a curve or may extend over only part of the distance between the two limit ordinates. This line is called the "solidus" and the regions between AE and EC on one hand and BE and ED on the other represent proportions of H and L which at the given temperatures are partly solid and partly liquid. It will be noticed that the point E lies both on the solidus line and on the liquidus curve, which would indicate that at the composition corresponding to E the metal solidifies throughout at the same temperature. This, as has been shown above, happens with the eutectic residue of H and L.

The solidification generally discussed above, namely, that of a mixture of two metals H and L which are supposed to form a system having a eutectic temperature but not producing a solid solution may now be considered in connection with the diagram of Fig. 1. The metal will remain entirely liquid until it reaches the liquidus line AE at Q. Then a certain amount of H will freeze and this will increase the percentage of L in the liquid mixture from $O.Q$ to $O.R$, but at $O.R$ the metal freezes at a lower temperature r. At that temperature a sufficient amount of H will have frozen to increase the percentage of L to $O.S$, and the freezing temperature will become s. The next step will carry the percentage of L to $O.T$ and the corresponding freezing temperature to t, and this will continue until the temperature C is reached, which is the *lowest temperature at which the mixture of H and L can freeze* and corresponds to the eutectic composition containing y per cent of L in the liquid mixture. From there on the freezing will proceed without change of temperature or of composition of the liquid metal, i.e., in the same manner as if it were a pure metal. It should be understood,

of course, that the steps *QR*, *RS*, *ST*, etc., which are shown in the diagram as large distances are really infinitesimal ones, the process being a practically continuous one instead of, as shown here diagrammatically, divided into three or four steps. In the case of alloys forming solid solutions the liquidus and solidus have the meaning explained in connection with Fig. 1, but the shape of the curves is entirely different. Samples of such curves will be found, for example, in Fig. 33 on p. 98 and Fig. 34 on p. 99 of Dr. Rosenhain's book cited above.

This matter of freezing of metals has a very practical importance in many ways. As an example of this the case of steel ingots will be considered here, particularly important because the great majority of the products used in engineering begin as an ingot—to

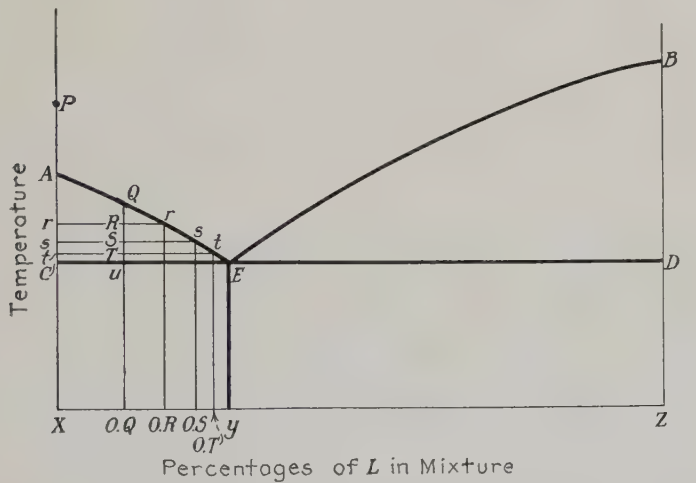

FIG. 1 IDEAL EQUILIBRIUM (CONSTITUTIONAL) DIAGRAM OF A SIMPLE BINARY EUTECTIFEROUS SYSTEM

be forged, hammered, rolled, drawn into the final shape, etc. Moreover, in particular reference to rolled and drawn products, it has been found that in drawing and rolling the qualities of the ingot are distributed throughout the length of the product, so that whatever metal there may be, for example, in the inside core of the ingot will invariably affect the structure of the inside core of every beam, channel, or rail rolled from that part of that particular ingot.

Steel ingots in the conventional system of manufacture are made by pouring molten metal into stationary steel or cast-iron molds, the size of the ingot varying in ordinary practice from about 6 in. by 6 in. by 48 in. for tool and special alloy steels to huge blocks weighing many tons for gun forgings. The majority of commercial carbon-steel products are made, however, from ingots

varying from, say, 16 in. on the side to about 48 in. on the side and about 72 in. long, although the larger ingots are cast in lengths up to 14 ft. The first molten metal teemed into the mold rapidly freezes, because of the contact with the cold mold wall. On freezing it contracts and draws away a little from the mold. It also gives up some of its heat (and some of the heat of the metal teemed subsequently into the mold) to the mold itself, causing the latter to heat and expand, as a result of which a certain air space is formed between the outer wall of the ingot and the inner wall of the mold, hindering to some extent the transfer of heat from the ingot to the mold. For various practical reasons, steel is teemed from the ladle into the molds at a fairly rapid rate from, say, $1^1/_2$ tons per min. in the case of gun-forging ingots to 3 tons and even higher for ordinary steel products. With the present large heats (up to 100 tons per ladle) and the urge to attain the largest possible production, fast pouring is desirable because it makes freezing in the ladle nozzle less likely and permits getting through with the heat quickly. As a result of it, however, the mold is filled very rapidly. How does the freezing of the metal proceed then? Obviously, as has been noted above, the metal in immediate contact with the mold wall and to a small depth therefrom freezes very rapidly. But the layer next to it can lose heat only through the outside shell of the ingot which is itself very hot and therefore does not take up the heat easily from the molten steel. Moreover this shell can lose its heat only by giving it up to the mold and stool. (The ingot mold is open at the top and bottom and sits on a heavy cast-iron base called a "stool.")

But as has been noted above, the transfer of heat from the ingot to the mold is somewhat slow, because of the presence of the intervening air spaces. Therefore the cooling of the metal in the interior of the ingot proceeds rather slowly, and, as a matter of fact, if a hole were drilled into the side of a five-ton ingot half an hour after it was cast, molten metal would "bleed" out of the hole.

Now, if molten metal chills slowly it will chill in the manner described above; that is, first the constituent having the highest melting point will separate out to some extent, leaving a material rich in constituents having the lower melting points. These will have a lower melting point than the first batch because of the greater content of the alloying elements, and this process will continue until the eutectic mixture of the higher-melting-point constituents and the lower-melting-point constituents has been reached, whereupon the freezing of the alloy will continue at a constant temperature equal to the freezing temperature of this eutectic mixture.

How will this affect the resulting steel in the ingot? Commercial carbon steel has for its main constituents iron and carbon. It also contains, however, such materials as oxides of iron, phosphides and sulphides, silicates, and possibly manganese phosphide and sulphide. All of these have melting points considerably lower than

that of the iron-carbon constituents, and as a result of the selective process of freezing described above they are gradually displaced to the last period of freezing in respect to time. But because of the method of freezing of an ingot, which proceeds from the outer shell inward, they are also displaced toward the central part of the ingot, which is therefore often richer in these impurities than the outer parts of the ingot. This process of concentration of some of the constituents of a steel in a given part is called "segregation." It is very undesirable, particularly in products subject to vibrational or alternating stresses, because the particles of segregated impurities not only do not contribute anything to the strength of the part of the metal in which they are embedded, but apparently on account of their irregular shape act somewhat like the notch in the notch impact test, introducing a grave weakening of the mechanical strength of the material.[7] (Compare paper by J. P. Snow entitled Some Features of the American Rail Situation, before the Sixth Congress of the International Association for Testing Materials, vol. 2, pt. 2, paper X9.)

Cell Formation in the Process of Freezing of Metals

Various tests also indicate that, at least under certain conditions, metal on freezing forms cells. G. Cartaud[4] poured readily fusible metals like lead, zinc, etc., over an inclined glass plate and so preserved the structure exhibited in Fig. 2 (magnified 300 diameters) for lead treated in this manner. The formation of these cells would seem to indicate that a similar process precedes solidification in all metals. These cells represent what are known as foam chambers which may (this is not certain yet) form subsequent boundaries of crystal grains. It is also possible that several foam chambers unite in crystal.

The foam walls enclosing the cells may be formed within the liquid alloy either by the material of the alloy itself or by solid substances such as solid oxides. If this happens the foam walls remain after solidification, disturbing the coherence and impairing the strength of the material. This may happen, for example, in mild steel if aluminum is added to the molten metal under certain conditions. The aluminum oxide resulting from the combination of the aluminum with oxygen is on account of its difficulty of fusion solid in the liquid mass of iron and forms foam walls that are still fusible after freezing. Iron containing such foam walls after freezing is not malleable but is crushed if the attempt is made to forge it at red heat. Many railroad specifications do not permit to use aluminum as a deoxidizer for rail steel.

Allotropic Modifications of Iron

We may now return to the subject of allotropic modifications of iron. Pure iron in its normal condition is extremely ductile and possesses magnetic properties. It is called "alpha" ferrite or

alpha iron. Upon heating this alpha iron to a little above 1400 deg. fahr. which corresponds to the critical range Ac_2, the iron becomes practically non-magnetic and is then known as "beta" iron. If it is further heated to a temperature above the upper critical range Ac_3, another change occurs producing "gamma" iron, which is somewhat softer than the beta iron. An understanding of this subject of allotropic modifications will assist in understanding the formation of the various constituents of steel. This latter also involves the subject of solid solutions. A solid solution may be pictured as a homogeneous union of two or more substances in indefinite proportions, this union persisting in the solid state and being so complete that the individual substances cannot be distinguished under the highest-powered microscope. Chemical com-

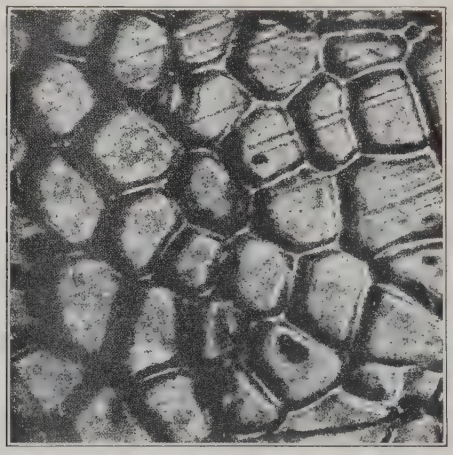

FIG. 2 STRUCTURE OF FUSIBLE METALS POURED OVER AN INCLINED GLASS PLATE (CARTAUD)

bination is not implied since a new compound would then be formed and the separate constituents would cease to exist as such, as they do in solid solutions.

It has, however, been shown above that where iron and carbon are present, carbon in amounts not exceeding a certain limit may unite with iron to form a carbide called "cementite," and that all carbon and iron in excess of that which goes into cementite stays free.

When pure iron undergoes its various allotropic transformations (the existence of the alpha and gamma iron is certain, and enough evidence is available to make the belief in the existence of the beta iron reasonable), there occurs merely a rearrangement of the iron molecules themselves, which means movements through comparatively small distances and hence requires but little time. If,

however, the same changes occur in iron containing carbide of iron, such as cementite, the carbide molecules have to change their places, and this means a fairly large movement. The process may be carried out in two ways, either slowly or with extreme rapidity. If the process is carried on slowly within certain ranges of temperature, cementite forms a mechanical mixture with a definite amount of ferrite so that the resultant will contain approximately 0.89 per cent carbon. This mixture is called "pearlite," because usually it consists of interstratified bands of ferrite and cementite having an appearance under the microscope somewhat like that of mother-of-pearl. If, however, the cooling takes place with great rapidity, as, for example, by quenching, and the carbon content is sufficiently high, traces of the undecomposed gamma solid solution remain as white structural streaks running across the needle-like general mass. This structure has received the name of "austenite," which is defined by the International Association for Testing Materials as the gamma-iron solid solution when preserved as such down to ordinary temperatures; which may happen either as the result of quenching or because of the presence of a third alloying element.

Under certain conditions austenite decomposes into a needle-like, crystal-like substance which is called "martensite." Some investigators claim that under certain conditions of quenching there is produced martensite of composition 0.89 per cent carbon which is structureless and is desirable in quenched steels of certain compositions, such as cutlery steel, where the presence of a definite martensitic structure would indicate overheating. Such structureless martensite has been called "hardenite." It is always produced under such conditions that its carbon content is approximately 0.89 per cent, eutectoid ratio. Quite recently (cp. *Revue de Métallurgie*, Feb., 1925) a new theory of the formation of martensite has been proposed by the Japanese metallurgist Kotaro Honda, who denies that martensite is a degeneration product of austenite.

Figs. 9 and 10 show martensite as it appears under magnifications of 100 and 500 diameters, and Fig. 11 shows it under a magnification of 1840 diameters. Martensite is very important as it is the hardest constituent of hardened steels. It is due to its presence that quenched steels are so hard. It varies widely in the details of its structure, but usually has a needle-like (acicular) appearance, although at times the needles may be exceedingly minute.

Of late a view has been offered (by Francis F. Lucas)[1] that it is the distribution of iron carbide in a highly dispersed state that is one of the contributing factors to hardness, if not the chief factor. According to this view the transformation to martensite marks in its early stages a very rapid precipitation of this constituent alloying with iron in some other allotropic form than the gamma state.

While it has been stated above that martensite usually appears under a microscope in the form of needles, it is also found with a

[1] Numbered references in text given at ends of chapters.

decidedly granular appearance. This may be due either to partial decomposition to "troostite" (see below), or to the fact that the needle showing the regular structure is sectioned on a plane almost parallel to the plane of a line structure.

FIG. 3 LARGE-GRAINED STEEL CASTING. MAGNIFIED 100 DIAMETERS

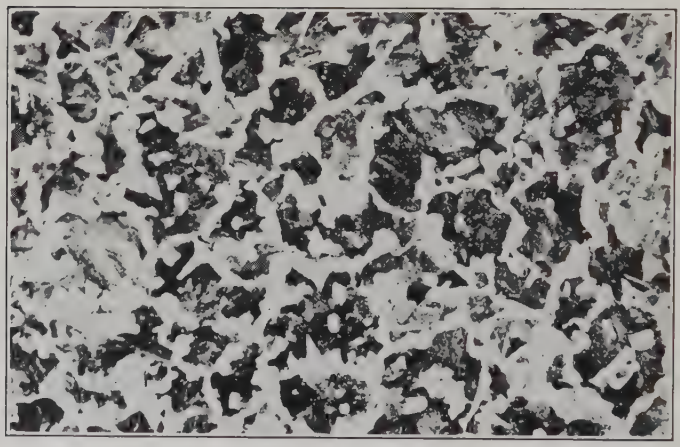

FIG. 4 SMALL-GRAINED STEEL CASTING, ANNEALED. MAGNIFIED 100 DIAMETERS

(Courtesy of Union Carbide and Carbon Research Laboratories, Long Island City, N. Y.)

It is shown above that austenite and martensite form in rapidly cooled, i.e., quenched, carbon steels. If the rate of cooling is somewhat slower, the resultant structure is different. The edges of the martensite grains, more particularly where they border upon

ferrite in steels containing less than the eutectoid proportion of carbon (0.89 per cent), show rounded or woolly outlines. This constituent on etching gives a very dark appearance, is called "troostite," and may be regarded as a further step in the degradation

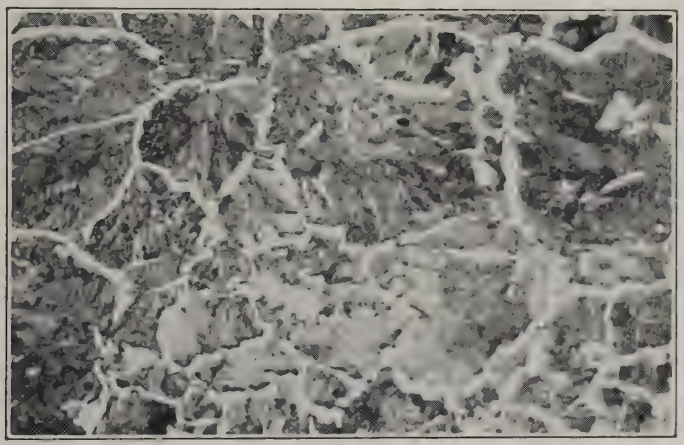

FIG. 5 PEARLITE. MAGNIFIED 100 DIAMETERS

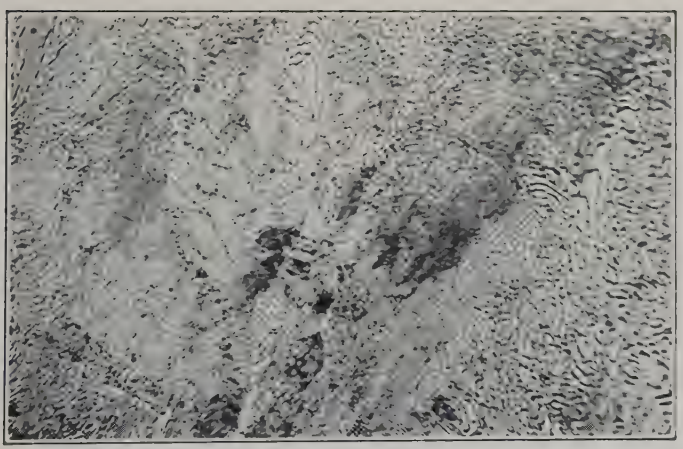

FIG. 6 PEARLITE. MAGNIFIED 500 DIAMETERS
(Courtesy of Union Carbide and Carbon Research Laboratories, Long Island City, N. Y.)

of austenite into ferrite plus pearlite (see Fig. 12). Troostite is a good deal softer than martensite and may be obtained either directly by a suitable rate of cooling or from martensitic steel (i.e., quenched steel) by reheating to a suitable temperature. This broadly explains why

the so-called tempering—of which more will be said in the chapter dealing with heat treatment—reduces the hardness of quenched steels. When the rate of cooling is slowed down still more as compared with that in the previous operation, or the temperature of

FIG. 7 SORBITE. MAGNIFIED 100 DIAMETERS

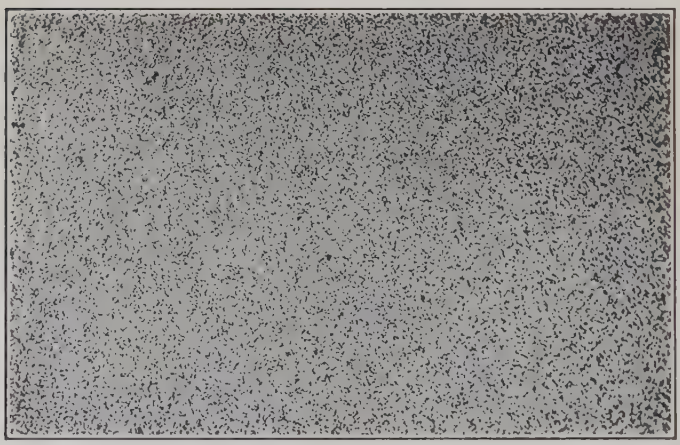

FIG. 8 SORBITE. MAGNIFIED 500 DIAMETERS
(Courtesy of Union Carbide and Carbon Research Laboratories, Long Island City, N. Y.)

reheating raised, the decomposition of austenite is carried still further and a constituent obtained which is devoid of any visible detailed structure under the highest available magnifications; moreover it does not etch to such a deep color as troostite and does not

have its peculiar rounded outlines. (See Figs. 7 and 8.) This constituent is called "sorbite," but some metallurgists claim that it is simply a variety of pearlite and that the dividing line between pearlite and sorbite is simply a question of resolving power. It may be

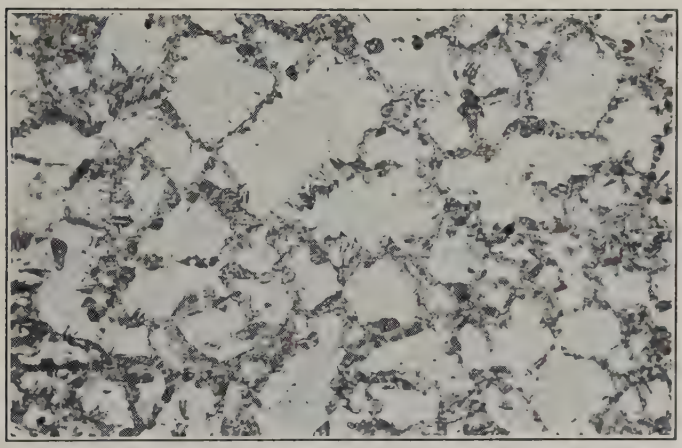

FIG. 9 MARTENSITE-TROOSTITE. MAGNIFIED 100 DIAMETERS

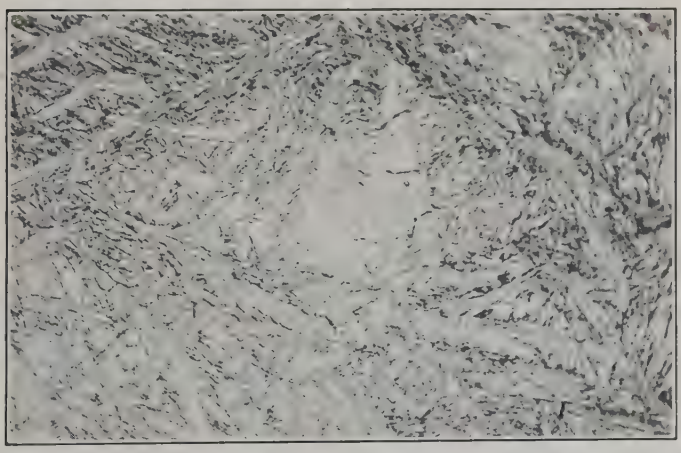

FIG. 10 MARTENSITE. MAGNIFIED 500 DIAMETERS (CP. FOR MARTENSITE FIG. 11)

(Courtesy of Union Carbide and Carbon Research Laboratories, Long Island City, N. Y.)

mentioned by the way in this connection that the names austenite, martensite, troostite, sorbite, and some others have been given to the various constituents of steel in honor of the founders of the science of metallography. Rosenhain[2] points out that as between martensite

and troostite on one side, and pearlite and sorbite on the other, there is a very important distinction: the two former are found essentially in steels quenched from temperatures above the line *PSK*, this line being the lower limit of existence of the gamma-iron phase (Fig. 16), while the latter are only met with if the rate of cooling through that temperature has not been unduly accelerated. Troostite is most readily obtained by oil quenching from temperatures just above *PSK* or 700 deg. cent., or by water quenching while

FIG. 11 DEVELOPMENT OF MARTENSITIC NEEDLES AT THE GRAIN BOUNDARY OF AUSTENITE. MAGNIFICATION, 1840 DIAMETERS

(From paper in Transactions of The American Society for Steel Treating, vol. 6, no. 6, December, 1924, by Francis F. Lucas; published by courtesy of the author of the paper and the Western Electric Company, New York City.)

the steel is actually in the critical range Ar_1. Rapid air cooling of steel specimens from temperatures above Ar_1 is sufficient to produce sorbite, which merges into pearlite as the rate of cooling is decreased (cp. *Colloid Chemistry and Ferrous Metals*, p. 27).

An interesting utilization of the metallurgist's ability to produce the desired structure in steel may be seen in the manufacture of the so-called "sorbitic" rails. From what has been said above, it would be reasonable to suppose that sorbite lying between marten-

site and pearlite would be softer and tougher than martensite but harder than pearlite. It would therefore be of advantage for materials subjected to stresses at the same time as wear, such as, for example, rails and railroad wheel tires, and sorbite production has been applied to these materials in the Sandberg process, which consists of heating the steel to a temperature above the critical point and then cooling it so slowly that the martensitic condition is not retained and yet sufficiently rapidly to offset the pearlitic

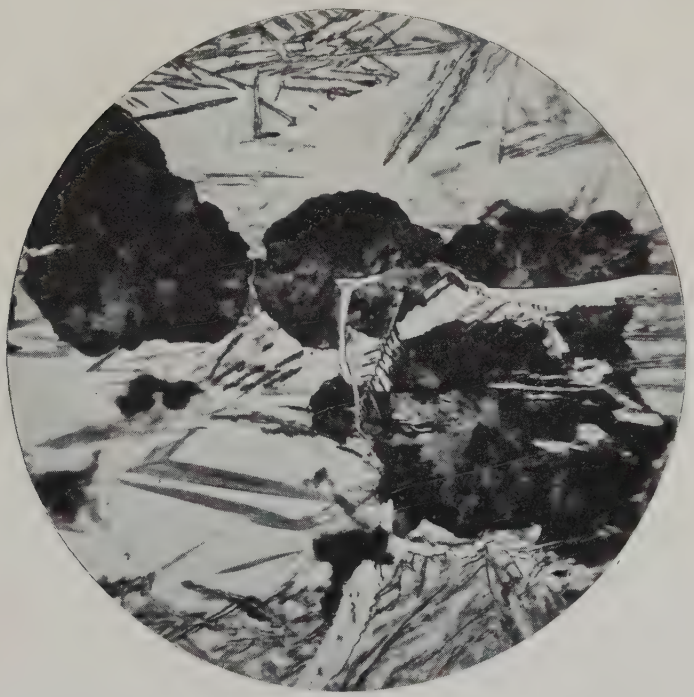

FIG. 12 NODULAR-TYPE TROOSTITE FORMED BY THE DIRECT DECOMPOSITION OF AUSTENITE TO TROOSTITE. MAGNIFICATION, 2400 DIAMETERS

(From paper in Transactions of the American Society for Steel Treating, vol. 6, no. 6, December, 1924, by Francis F. Lucas; published by courtesy of the author of the paper and the Western Electric Company, New York City.)

stage's being reached. The cooling is done by blowing air or steam on the heated steel. Tests have shown that fully treated steel had a breaking stress of 76.4 tons per sq. in. as compared with 57.32 tons for steel cooled in the atmosphere.[3]

It has been shown above that a mixture of ferrite and cementite in such proportions as to constitute pearlite contains 0.89 per cent carbon. Such a steel is known as a "eutectoid" steel. "Eutectoid," or "quasi-eutectic," is a term used to described the solid-solution

alloy of the lowest transformation point; in other words, the mixture of materials separating in the solid state along the horizontal line of the equilibrium diagram at the eutectic point. Steels containing less than 0.89 per cent carbon are also built up of ferrite and cementite, but some of the ferrite is not mixed with the cement-

Fig. 13 Piece of Forging Showing Lamellar Pearlite

ite to form pearlite and is therefore free. Such steels are called "hypo-eutectoid," hypo in Greek meaning "under," and indicating that the steel contains less than the theoretical limiting carbon content.

Pearlite is usually encountered in lamellar form. The ductility of such a pearlite is, however, very low. It has been found that

by means of a "loneal" (heat treatment carried out by heating below the critical temperature—the meaning of this is explained in Chapter IV—followed by cooling) the cementite may be converted into the form of small rounded globules. Such a cementite is called "spheroidized." There is still some doubt as to the mechanism

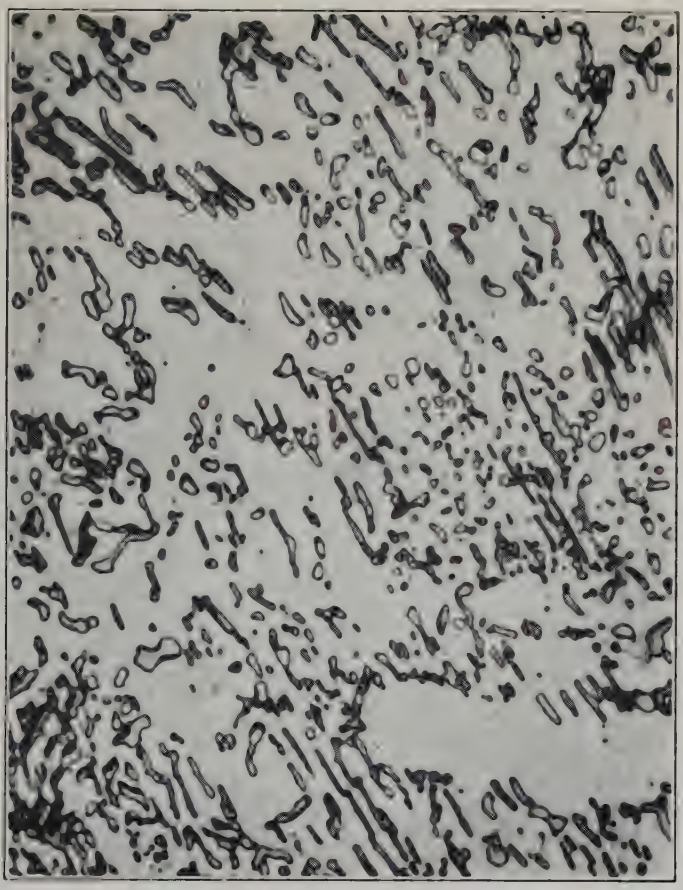

FIG. 14 PIECE OF SAME FORGING AS IN FIG. 13, SHOWING PRACTICALLY COMPLETE SPHEROIDIZING OF THE CEMENTITE

by which spheroidized cementite is obtained. It would appear certain, however, that with proper heat treatment it greatly increases the ductility, especially in transverse and radial tensile test bars.[6] Fig. 13 shows typical lamellar pearlite after an anneal of 1475 deg. fahr. for 8hr. The ductility is very low (this was taken

from a forging $24^{1}/_{8}$ in. in diameter, $180^{11}/_{16}$ in. long, made from a 31-in. ingot, test bars taken radially). A further treatment of 1250 deg. fahr. for 56 hr. shows an increase in ductility and the practically complete spheroidizing of the cementite of the pearlite (Fig.

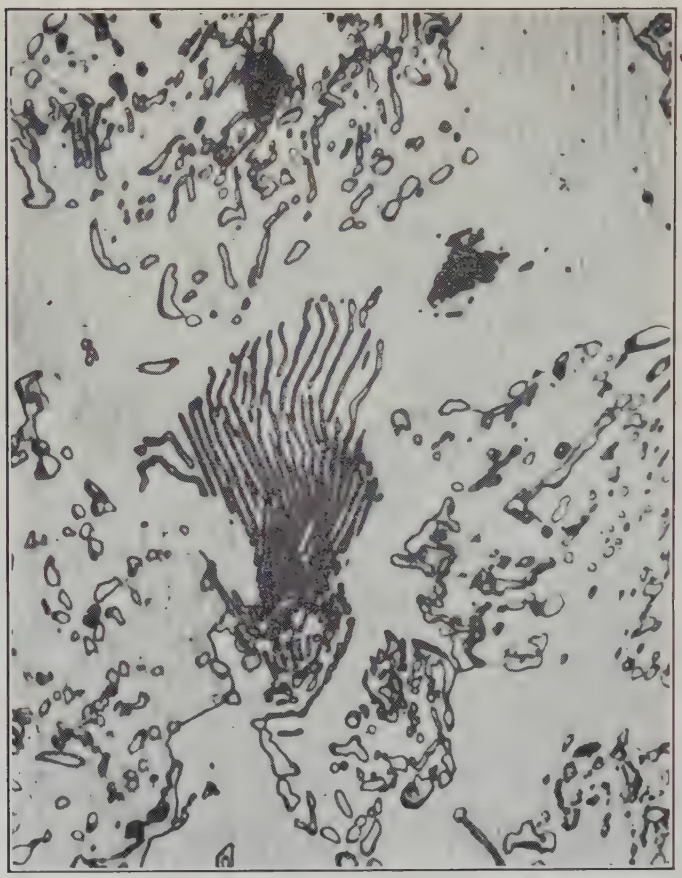

FIG. 15 SAME PIECE AS IN FIG. 14, SHOWING SPHEROIDIZED CEMENTITE AND ALSO CEMENTITE LAMELLAE

14). Fig. 15 shows an area evidently of lower or more uniform concentration with portions of the cementite lamellae still undissolved.

TABLE 1 DATA OF PHYSICAL TESTS OF STEEL SHOWN IN FIGS. 13 AND 14

	Fig. 13	Fig. 14
Yield	38,500	32,200
Ultimate	84,000	66,000
Per cent elongation	18	27
Per cent reduction	26	42

When the carbon content exceeds 0.89 but is less than, say, 1.7 per cent, there is more cementite present than can mix with the ferrite. Such steel consists then of pearlite with free cementite, the amount of cementite increasing with the carbon content. Such steels are called "hyper-eutectoid" (hyper meaning "above"). Finally a point is reached when the iron is no longer capable of combining with the carbon, and if more carbon is present in the material than the iron can combine with, this carbon will be trapped when the iron solidifies and will be present in the iron in the form of free carbon. In the constitutional diagram, Fig. 16, this is represented by the region lying to the right of *E*.

This will be discussed in a separate chapter.

The Iron-Carbon Equilibrium Diagram

The curves of Fig. 1 represent an ideal equilibrium diagram of a simple binary eutectiferous system. The iron-carbon system, however, has a somewhat more complicated diagram, of interest not only because of the importance of iron-carbon alloys, but also because more study has been devoted to this diagram than to that of any other metal or alloy.

The diagram of Fig. 16 is reproduced from a report of Committee 53 on the Nomenclature of the Microscopic Substances and Structures of Steel and Cast Iron, presented by Professors H. M. Howe and A. Sauveur to the Sixth Congress of the International Association for Testing Materials (New York, 1912, paper II–7, p. 6). This diagram extends only to a carbon concentration of 5 per cent, which is the practical limit of carbon found in iron alloys. (Experimentally, alloys with higher carbon content have been prepared, however.) It deals with a system which differs from that shown in Fig. 1 in that it forms a solid solution. Some lines have been added to the original diagram.

It appears from this diagram that all metal above *ABC* is liquid, the line *ABC* being the liquidus of the diagram. All material below *AED* is solid, the limit of solid solubility of cementite in iron lying on the point *E* or at about 1135 deg. cent. The point *B* lying on both the liquidus and the solidus is the eutectic point, in this case that of the solid solution of γ iron with cementite.

The line *ES* shows the limit of solid solubility of cementite in γ iron. There are two features about it worthy of notice: one is that it slopes downward toward the low-carbon end of the diagram, which would indicate that the amount of cementite which γ iron can retain in solid solution decreases with falling temperature. The other feature is that the line *ES* does not extend to the base of the diagram, due to the fact that γ iron does not exist in a state approaching equilibrium below the temperature indicated by line *PSK*.

Dr. Walter Rosenhain in the constitutional diagram of the iron-carbon system on page 161 of his Introduction to the Study of

Physical Metallurgy, adds a line shown in Fig. 16 as *ST*. To the left of this line and below *PSK* the metal consists of iron and materials of degeneration of austenite, which, as has been stated above, depending on the rate of cooling or thermal treatment, may be martensite, troostite, sorbite, or pearlite, which are varying arrangements that had been explained above. (In the original

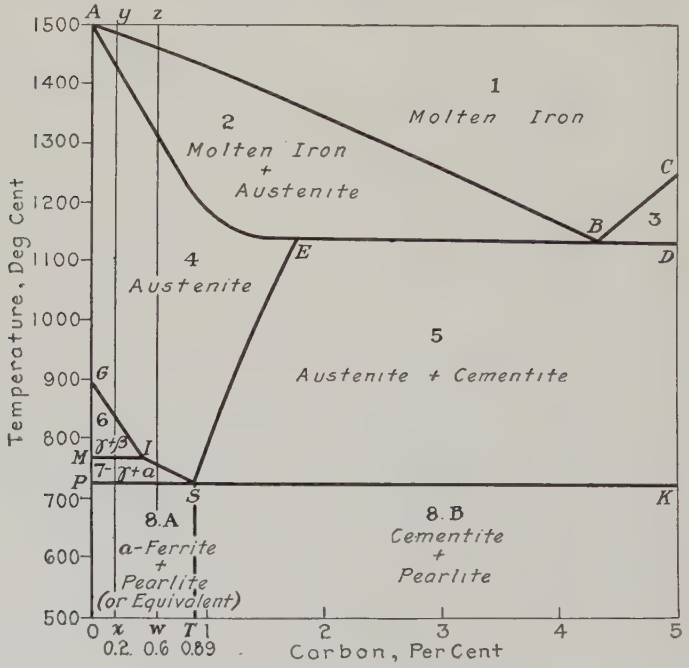

Fig. 16 Constitutional Diagram of the Iron-Carbon System

diagram this is designated as α ferrite and pearlite; as other constituents than pearlite may be also present, it is marked in this diagram α ferrite + pearlite, or equivalent.)

To the right of *ST* the metal may consist of cementite + pearlite with or without free graphite in either globular or flake form, depending on the factors discussed elsewhere (see Chapter V on Cast Irons). But on the line *ST* the metal consists of pearlite only as this line corresponds to the eutectic composition. Because of this the point *S* may be called the "eutectoid" point, and the body formed along the line *ST* is a "eutectoid."

To give an idea of the information that a diagram of the kind shown in Fig. 16 may supply, steel containing 0.2 per cent carbon may be considered. It may be mentioned, however, in this connection that this discussion should not be taken as completely

covering the subject; more information on the same subject will be contained in the second and third chapters, dealing respectively with the crystalline structure of ferrous metals and the thermal treatment of ferrous metals.

At a temperature of 1500 deg. cent. indicated by the point *y*, the metal is entirely molten. Beginning with the point where *yx* crosses *AB*, the metal begins to solidify, so that between that point and the point where *yx* crosses *AE* we have a mixture of molten iron and austenite, the solidification proceeding in a manner somewhat though not absolutely similar to that indicated in our discussion of Fig. 1. From the point where *yx* crosses *AE* to the point where it crosses *GI*, the entire metal is solid and is a mixture of austenite (which is a solid solution of carbide of iron in gamma iron) and gamma iron. When the metal cools down to the temperature corresponding to the point where *yx* crosses *GI* (about 840 deg. cent.) a change occurs in its structure in that some of the gamma iron is deposited out in the form of beta iron. It may be repeated in this connection that some doubt has been expressed as to whether beta iron is a true allotropic modification of iron. This hinges largely, however, on the definition of what an allotropic modification is and need not be discussed further here. Dr. Walter Rosenhain, for example, believes that beta iron is a true phase of iron, intermediate between the gamma phase and the alpha phase (Introduction to the Study of Physical Metallurgy, 1923, p. 170). Beta iron exists only between the temperatures corresponding to the points where *yx* crosses *GI* and the line *MI*. Below that temperature all the beta iron is transformed into alpha iron, so that in the section between *MI* and *PS* we have a mixture of gamma-iron solid solution with a steadily increasing content in crystals of alpha iron. As the line *PS* is passed (about 750 deg. cent.) the gamma-iron solid solution is transformed into the eutectoid mixture of alpha iron and cementite (which is pearlite), so that the metal consists of alpha ferrite and pearlite.

We know, then, that this metal has three points of transformation: first, on crossing *GI* from gamma into beta iron, second, on crossing *MI* from beta into alpha, and third, on crossing *PS* from gamma-iron solid solution into pearlite. The line *wz* which corresponds to the steel containing 0.6 per cent carbon crosses only the lines *IS* and *PS*, so that instead of having three transformation points it has only two and does not pass at all through the beta phase. In a later chapter dealing with the subject of heat treatment, the practical importance of this difference of behavior of the two steels will become evident, and among other things it will be shown how use is made of the fact that the 0.6 carbon steel line crosses the *AE* line lower than the 0.2 carbon steel line. This is merely cited to illustrate the use to which the constitutional diagram may be put, and the subject will be discussed more fully in later chapters.

Pearlite in Gray Cast Iron

The constituents appear somewhat different in cast iron from what they do in steel. Pearlite in steel consists essentially of ferrite and cementite. In cast iron the pearlite contains also certain impurities in a state of solution in the ferrite (silicon and phosphorus). Furthermore, pearlite may be found directly in contact with graphite.

The condition of the pearlite in cast iron is governed by a number of factors, some dealing with foundry practice and therefore outside the scope of the present discussion, and some with a composition of metal. Moderately high manganese is of considerable help in retaining the combined carbon in a suitable form, but chromium is far more effective when added in excess of 0.3 per cent. In such a cast iron the graphite flakes are all small and completely embedded in the sorbitic ground mass right up to their borders, which show no ferrite separations at all. Phosphorus is one of the most powerful elements in affecting the structure of iron. Where phosphide of iron is found in either partially or wholly pearlitic cast iron, these are apt to be brittle, especially when the rate of cooling has been sufficiently slow to permit of the phosphide segregating into rather large patches. When the phosphorus content of an otherwise all-pearlite cast iron reaches 0.4 per cent it is apt to form isolated patches of the eutectic instead of the much more preferable meshwork which usually occurs when the phosphorus is kept below 0.3 per cent, even if the cooling rate is practically identical for the same section of metal casting.

Graphite in Gray Cast Iron

In the average gray cast iron the graphite content amounts to about 10 per cent by volume. It is necessary, therefore, to regulate the form and distribution of the graphite so as to interfere as little as possible with the properties desired of the fundamental structure. Older views held that upon cooling a melt of cast iron, carbide was first formed. After solidification this decomposed into graphite, the system passing from a metastable to a stable state. Recent investigations have shown, however, that graphite is formed directly from the melt, the graphite eutectic temperature being 7 deg. higher than that of the carbide. If minute crystals of graphite remain undissolved in the melt, the formation of the graphite eutectic is assumed due to seeding. Passage into the metastable carbide system, by supercooling, is thus prevented. The separation of graphite is analogous to other crystallizations, depending upon the number of crystal nuclei present, the speed of crystallization, and the degree of cooling. The absence of nuclei leads to a high degree of supercooling with the subsequent formation of many small crystals. It is desirable in casting gray iron to avoid supercooling below the graphite eutectic temperature. This gives graphite nuclei a chance to form or grow, and prevents them

from passing into the metastable carbide system. Should the latter take place a reheating will result in the decomposition of carbide and considerable amounts of carbon will be formed. Bardenheuer shows by a series of experiments accompanied by photomicrographs that this carbon appears in the form of nodules of so-called temper carbon, the temperature of decomposition having been below that of the graphite eutectic. This is contrary to the opinions of Northcott, Honda, and Murakami, who hold that normal flaky graphite is formed by decomposition of Fe_3C after solidification. Bardenheuer also finds, contrary to Northcott, Honda and Murakami, that upon quenching a sample of melted gray cast iron from 1300 deg., graphite is formed. His conclusion is that normal graphite is never formed except by solidication from a liquid melt. The formation of graphite is most favored in iron of the eutectic composition for here the longest cooling halt occurs at the optimum temperature for graphite formation. All other things being equal, the lower the carbon content the smaller will be the crystals of graphite separating out. If the melt be overheated to, say, 1500 deg., complete solution of all graphite crystals and nuclei may result, with the consequence that on cooling a high degree of supercooling will be attained. The result may be many fine crystals of graphite. Rapid cooling in this case would yield Fe_3C, and by its decomposition, temper carbon. In the latter case the amount of free carbon present depends entirely upon the rate of decomposition of the Fe_3C. The presence of silicon, aluminum and nickel are found to favor the separation of graphite. Sulphur, manganese, and chromium increase the stability and favor the formation of the Fe_3C. Bardenheuer presents the results of tests to show that the finer the state of subdivision of the graphite in gray cast iron the higher will be its tenacity. Chilling and reheating with the formation of finely distributed temper carbon yields even higher tenacity and a high degree of elasticity. A gray cast iron containing finely dispersed graphite will take a high, impenetrable polish, in which condition the metal is often superior to expensive alloyed irons in its resistance to chemical corrosion.[8]

Colloid Chemistry and Ferrous Metals

It has been shown in the preceding chapter that under the influence of certain heat treatments, steel gradually passes from one structure to another, beginning with, say, austenite through martensite, troostite, sorbite into pearlite, and that it is possible (with certain limitations) by various means to arrest the transformation of the metal at any given point and to have the desired structure retained in the metal. It has not been explained, however, what is the precise mechanism of these changes. As a matter of fact, it is not quite clear yet what this mechanism is. Some information is, however, becoming available and this will be presented here

with a strict warning that in what follows we are dealing with theories which, while apparently sound, have not yet been confirmed sufficiently by observation to be considered as definitely established. It would appear from them that at least some of the changes in the structure of metals referred to above belong to what is known as the class of phenomena of colloid chemistry.

Graham in the middle of the nineteenth century was the first to establish by various means that there are two classes of solutions, one of which he called crystalloid and the other colloid. If we throw a large lump of salt into water and agitate the water the salt will gradually "dissolve," which means that particles of salt will be torn off from the lump and will enter into certain combinations with the water. If we throw in a large lump of salt the velocity of solution will be slower than is the case when we throw into the water the same salt finely powdered, but the ultimate result will be the same, namely, the salt (provided there is sufficient water) will be dissolved. If, however, we throw in a large piece of rock, to all practical purposes there will be no dissolving in water, no matter how long the rock may remain in the liquid and how strongly the liquid may be agitated. If, however, we break up the rock into finer and finer particles and throw these particles into the water, we shall notice that as the size of the particles decreases, they sink to the bottom with diminishing velocities, and finally a stage is reached when the particles do not sink at all but remain in suspension in the liquid. The case of salt in water Graham called "crystalloid solution." The case of rock in water when the particles have become so minute that they no longer fall to the bottom, Graham called "colloid solution."

In this connection a certain special terminology is used in order to distinguish the two kinds of phenomena. Colloidal solutions are referred to as "sols," a word being added to define the solvent material; thus, solutions in water are called "hydrosols;" solutions in alcohol, "alcosols," etc. Under certain conditions the suspended matter is thrown out of the colloidal solution similarly to what happens when salt crystallizes out of water in crystalloid solutions. The material thus precipitated is called a "gel," while the process of returning the gel to the state of colloidal solution is called "peptization."

There are two ways of producing colloid solution. One is by breaking larger particles of matter into particles so small that they can be held in suspension in the liquid. This method is called the "dispersion method." Another way is by starting with particles approaching the molecular size or with matter in the gaseous state, and coagulating them until they become of a size forming colloid solutions. This process is called the "condensation process."

Coming now to the various forms in which iron appears, such as austenite, martensite, etc., it is claimed by C. Benedicks, W. Ostwald, and their comparatively few successors in this field[5] that aus-

tenite, martensite, etc., down to pearlite, represent merely various states of colloid dispersion. Austenite, martensite, and, under certain circumstances, hardenite, are most highly dispersed solutions approaching the molecular phases, their extremely high dispersion being due to rapid cooling. Pearlite is the product of slow cooling and represents the minimum of molecular dispersion, passing, in the case of lamellar cementite, possibly out of the range of colloid solution into the territory of gels. Troostite and osmondite are located between these extremes, representing solid colloid solutions. According to this view, troostite is a colloid solution of cementite in ferrite brought about by the coagulation of the extremely fine dispersed particles of the previous forms, such as austenite and martensite, while pearlite represents the coarsely dispersed or coagulated ferrite-cementite sol.

An interesting comparison may be seen between steel and ruby glass. The latter is produced by adding chloride of gold to the bath of molten glass. As long as the gold in the glass is in the state of molecular dispersion it remains invisible and the glass is colorless. Through tempering (reheating the glass from a lower temperature) the gold molecules coagulate into colloid particles, giving the glass the beautiful ruby color of colloid gold. Tempering steel creates troostite obviously by producing corresponding changes in the dispersion phase of the particles of cementite.

There is another group of phenomena in colloid chemistry that may become of surpassing interest to ferrous metallurgy, namely, the so-called "protective" action of sols. One of the best examples of this is the action of gelatine on gold sols. Red gold sol may be coagulated by sodium chloride, in which case its color changes to blue. If, however, a sufficient amount of gelatine is added, no change in color takes place.

Now, if only we could find a material that would act in steel in the same "protective" manner as gelatine acts in the case of red gold sol, it would be possible to roll steel in such a manner as to retain at the end of the process the exactly desired structure, such as troostite for steel to be used in springs, sorbite for rail steel, etc.

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CHAPTER II

THE CRYSTALLINE STRUCTURE OF FERROUS METALS

Substantially all ferrous metals are crystalline in structure. The impression prevalent at one time that wrought iron is fibrous is due to superficial observation which shows streaks of metal interspersed with streaks of slag. Another impression, namely, that repeated shocks, vibration, or the application of excessive alternating stresses produce "crystallization" in metals is likewise erroneous as all ferrous metals are crystalline to start with. It will be shown later, however, how repeated alternating stresses do cause weakness by affecting the crystalline structure of the metal, though not by creating it. Because of the fact that many mechanical and chemical properties of ferrous metals depend on the state of crystallization, this subject assumes considerable importance to the mechanical engineer.

Crystals in General

The atomic theory of today teaches us that in a solid body the atoms tend to move in closed paths about fixed equilibrium positions. In the past it was believed that these equilibrium positions might possess a special regularity in arrangement or might not; if they did, the body was called crystalline; otherwise it was classed as amorphous. This view has not been completely set aside. Nevertheless within the last two years enough new evidence has been accumulated to make it appear doubtful whether or not there is such a thing as an amorphous body. More and more of the bodies which have been classed as amorphous have been found to be really crystalline, and, for example, Professor Katz of the University of Amsterdam has found that natural rubber is not amorphous, as has been hitherto assumed, but crystalline. While the following has not been proved by any means, it would nevertheless appear that there are bodies coarsely crystalline, i.e., such wherein the crystalline structure can be easily disclosed, as, for example, by a microscope of medium power. Next, there are finely crystalline bodies which only special skilled observation through more than usually powerful apparatus discloses, and it is not at all impossible that even those bodies that appear to be amorphous merely consist of crystals so fine as to be beyond even our best methods of observation.

A crystalline body (using the word "crystalline" in the commonly accepted sense) throughout which the special regularity of arrangement is undisturbed constitutes a single crystal. In a perfect crystal the same symmetry characteristics are maintained, no matter what may be the absolute size of the specimen. Thus, if a large rhombohedral fragment of calcite is split into bits by suc-

cessive blows it will cleave into many minute rhombohedrons, each of which possesses the same symmetry properties as the original piece.

The fundamental symmetry characteristics of crystals is shown by a study of the distribution of their plane faces and of various physical properties, such as refractive indices, which are unlike in different directions, and also by the behavior of extremely short (X-ray) waves when passing through crystalline bodies. In this way certain elements of symmetry have been recognized as present in crystals. The first and most important are the axes of symmetry. If in a figure a rotation along some line combined with translation along its length leaves the figure in its original geometrical aspect, the figure is said to have a "screw" axis of symmetry. But if the amount of the translation is zero, the symmetry axis is a simple rotational axis of symmetry. In crystals only certain axes are observed.

Next come the planes of symmetry, a plane of symmetry being defined as any plane that can be passed through a figure so that every point upon one side of the plane has a corresponding point on the other side in a mirror-image relation to it.

There are also centers of symmetry in crystals, a point being a center of symmetry if a line drawn from any other point of the figure to it and extended an equal distance beyond encounters a point corresponding to the arbitrarily chosen point.

Investigation has shown that there are but thirty-two distinctive ways of taking these elements of symmetry singly and of combining them together. From this a number of groups have been built up, each of which represents a system or class of crystals. In fact, the whole important science of crystallography has been reared on this foundation. However, only certain comparatively simple crystal structures are encountered in the case of commercially known metals.

The Internal Structure of Crystals

Such elements of crystal structure as the axes, planes, and centers of symmetry deal with the symmetry exhibited by a crystal as a whole. When we come to the subject of the internal symmetry of crystals, which is the question of the special grouping of symmetry elements, it is found that these are affected by the symmetrical patterns in which the groups of points are distributed. These symmetrical patterns are called "space lattices." A space lattice consists of a series of points in space, such that every point is situated symmetrically to every other point; space being usually imagined as divided into cells by three sets of parallel planes, with the planes of each set at equal distances from each other and parallel to each other.

The distances between planes may be different in the various systems and the three sets of planes may form any angles with each other. The points of intersection of these planes constitute

a space lattice. Taking, for example, Fig. 17, we have here a portion from a "body-centered"* cubic space lattice and the cube *OABCD-EFG* is a unit cell. For many purposes, including all those of crystal analysis, the unit cell may be taken as the smallest volume which will build up the entire grouping when repeated indefinitely by simple translations along the axes of coordinates.

The space groups define the positions that can be occupied by the atoms in crystals. If an atom is located at a certain point which we may call *XYZ* within a crystal, there must be exactly similar atoms at each of the equivalent points within the unit domain of its corresponding space and at the equivalent points arising from a repetition of this unit along the axes of reference. Measurement of the X-ray diffraction effects from crystals seems to show that the number of chemical molecules associated with the

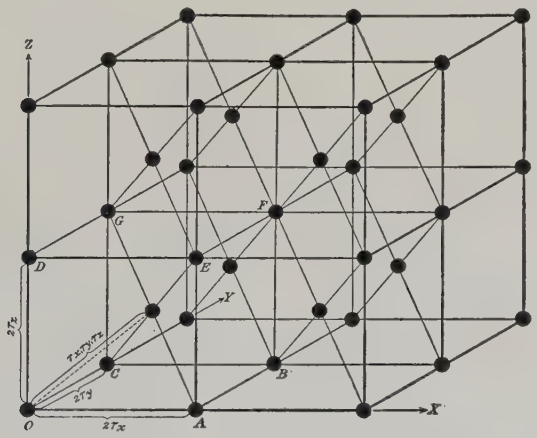

FIG. 17 A PORTION FROM A "BODY CENTERED" CUBIC SPACE LATTICE

(The cube *OABCDEFG*, with which are associated two points in the lattice, is the unit cell. Reproduced from Fig. 48, p. 59, of the Structure of Crystals, by Ralph W. G. Wyckoff, American Chemical Society Monograph Series, by courtesy of the publishers, Chemical Catalog Company, Inc., New York City.)

unit cell is usually small, and means have now become available to determine the number and location of the atoms within the crystal structure.

The arrangement of atoms in metal crystals appears to be simple. The simplest is that of a cube with an atom at each corner. This is what is known as the "simple cubic arrangement." No metals have been found to possess this arrangement, but it is encountered in salts composed of equal numbers of positive and negative ions

* This term is explained later.

such as the alkali halides. The arrangement encountered in metals, iron in particular, is that of a cube with atoms at the corners of a system of equal, closely packed cubes and an additional atom either in the center of each cube face or in the center of the cube itself. The former is known as the "face-centered cubic arrangement" of atoms and is illustrated at the right in Fig. 18, which represents the crystalline structure of gamma iron according to Westgren and Lindh;[1] the latter is the "body-centered cubic arrangement" of atoms and is shown at the left in Fig. 18, representing the crystalline structure of alpha and beta iron according to the same authorities. The face-centered cubic arrangement may be considered as formed by two simple cubic lattices intersecting each

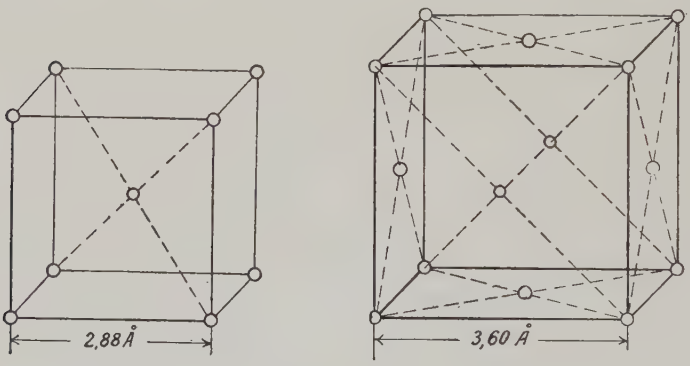

FIG. 18 CRYSTAL STRUCTURE OF ALPHA AND GAMMA IRONS (WESTGREN AND LINDH)
(*Eisen* = Iron.)

other in such a manner that the corner atoms of one lattice fall at the centers of the faces of the other lattices, so that any particular set of atoms may be equally well regarded as corner atoms or as face atoms. Each atom is surrounded by twelve equidistant and symmetrically situated atoms. This arrangement, illustrated in Fig. 19, is one of two which furnishes the closest possible packing for a number of equal cubes. It is sometimes referred to as the "cubic close-packed arrangement." In the body-centered arrangement illustrated in Fig. 20 (Hull) the corner atoms and center atoms are interchangeable, so that if the system of lines of Fig. 20 had started with one of the center atoms, all the corner atoms would become center atoms, and vice versa. Each atom is surrounded by eight equidistant and symmetrically situated atoms. This arrangement is not so closely packed as the face-centered arrangement.

From various investigations it would appear that iron at room temperatures has what is known as a body-centered cubic arrange-

ment of crystals, essentially such as shown in Fig. 20 and at the left in Fig. 18. From what has been said in Chapter I on the physico-chemical properties of iron, it would appear that this corresponds to the structure of alpha iron. Measurements (Westgren[1]) have also shown that the cubes measure 2.91 Ångstrom units (each such unit is 10^{-8} cm.) on a side. A similar investigation has shown that iron in the beta range of temperature has the same space lattice, i.e., body-centered cube, as alpha iron, but that the side of the elementary cube is slightly larger, which can be accounted for by the expansion of iron at the temperature of 830 deg. cent. at which the beta lattice was measured. It may be pointed out in this connection that the difference between the properties of alpha and beta irons is so slight that for a long time there has been a good deal of doubt as to whether two such allotropic modifications really existed. There has never been much doubt as to the existence of the gamma-iron allotropic modification, as the properties of gamma iron are clearly different from those of alpha or beta iron. This is very well accounted for by the observation of the crystal of gamma iron, as at 1000 deg. cent. it has a face-centered cube somewhat larger than that of alpha iron, namely, 3.61 Ångstrom units.

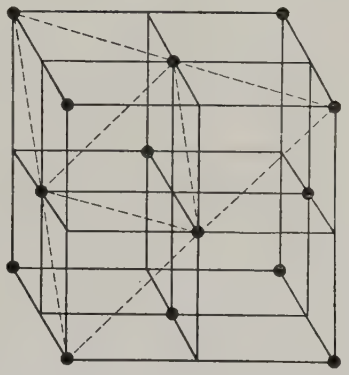

Fig. 19 Face-Centered Cubic Arrangement of Atoms (Hull)

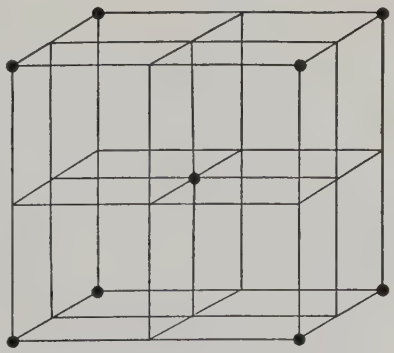

Fig. 20 Body-Centered Cubic Arrangement of Atoms (Hull)

A fact not new but none the less remarkable has been apparently established by an investigation made by Dr. Arne Westgren and G. Phragmen, who found that when austenite is heated through the uppermost critical point (about 1400 deg. cent.) it undergoes another modification (into what is designated as "delta iron"), and that this modification, like alpha iron, is body-centered.

At first glance it may seem strange that iron on cooling

starts with a body-centered structure of δ iron, then passes to a face centered γ iron, only to return subsequently back to the body-centered structure in β iron, assuming that there is such a phase, and in α iron. From the diagram of Weiss and Foëx,[12] where magnetic susceptibilities of iron are plotted as functions of the temperature, it would appear, however, that the part of the curve corresponding to the δ-phase is a direct continuation of the α-β phase line, while the part representing the γ-phase is simply "lifted out" or projected on to another level, Fig. 21.

In Chapter I reference was made to allotropic modifications of iron, or iron that without changing its chemical constitution appears in materially different forms as alpha iron at one time, gamma iron at other times, and possibly beta and delta iron under still different conditions. A glance at Fig. 18 will easily explain why this happens, alpha iron being body-centered and gamma iron face-centered cubic crystals without apparently any change taking place in the atoms constituting the different arrangements.

The theory that austenite, when heated through the uppermost critical point, undergoes a modification to delta iron, and that this modification, like alpha iron, is body-centered, is confirmed by E. C. Bain's work on the nature of the alloys of iron and chromium,[17] Bain having found that it is possible to develop and preserve delta-iron solid solutions at room temperatures. In this case chrome-iron alloys are used. They are heated above the range for austenite formation; upon quenching in water the transformation to austenite is suppressed and the delta-iron solid solution is preserved engaged in a permanently stable form identical with alpha-iron solid solution.

Among the observations made during this study was that of the high solubility of carbon in delta iron at high temperatures (in excess of 1400 deg. cent. or 2550 deg. fahr.). It is scarcely to be considered that at such a temperature any phase could long remain supersaturated, and yet in an alloy of 20 per cent chromium, polyhedral grains of delta-iron solid solution have been preserved at room temperature without a trace of carbide precipitation when the alloy contained 0.50 per cent carbon. Upon reheating such grains of delta iron at 750 deg. cent. (1380 deg. fahr.) the excess carbide is precipitated within the grains.

Bain gives a definition of delta iron, in the sense that delta iron signifies only that the material has been heated to a higher temperature than permits austenite to exist in contrast to alpha iron, which latter is a material which has been transformed from austenite by cooling through the transformation temperature at a proper rate. Physically the two are identical. From this investigation it would appear that alloys containing more than about 25 per cent chromium are without transformation, alpha-iron and delta-iron solid solutions being continuous and identical. With this chromium content carbon in excess of 0.40 per cent is required

to produce an appreciable amount of austenite at any temperature.

According to Westgren and Lindh,[1] high-speed tool steels hardened at 1275 deg. cent. have practically the same crystalline structure as alpha iron. As regards the structure of martensite, of importance in hardened steels, a recent investigation by K. Heindlhofer[10] would appear to show that martensite has a body-centered lattice like that of alpha iron, but the lattice is contracted about 0.4 per cent on a side and is also distorted. This distortion disappears largely, however, after heating the martensite at 260 deg. cent. for 30 minutes, although the hardness is not much decreased. From a comparison of the densities of specimens of martensite with those of alpha iron and of cementite, it would appear that martensite is

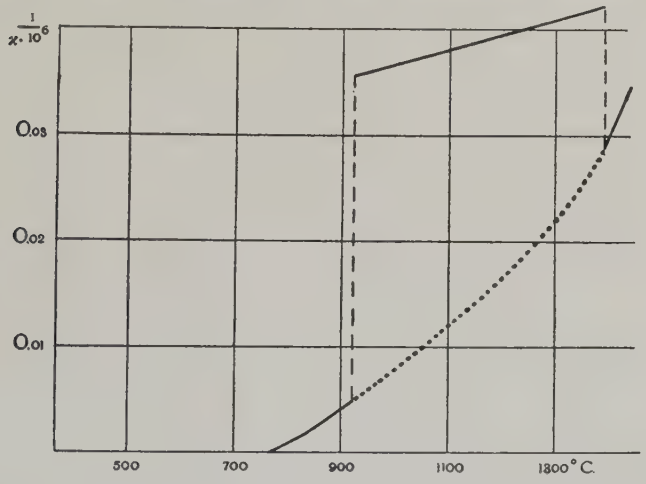

FIG. 21 VARIATION OF MAGNETIC SUSCEPTIBILITY OF IRON WITH TEMPERATURE (WEISS AND FOEX)

a mixture of (1) a solid solution of carbon in iron, the C atoms replacing the Fe atoms, and (2) of finely dispersed cementite, the former being unstable even at room temperature. Both seem to contribute to the hardness, the solid solution by distorting the lattice, and the cementite by being so fine-grained.

The structure of martensite cannot be considered to be definitely established as yet. In this connection an interesting paper has been published by Hanemann and Schrader,[18] which originally appeared in German.[19]

In this paper the authors first present a review of previous investigations regarding the structure of martensite and austenite in hardened steels, their thermal expansion, and critical points. The current opinion based upon these investigations is that martensite is alpha iron whose space lattice has been strained by an un-

stable solution of carbon within the lattice. The authors point out that the established facts of the austenite-martensite reaction cannot be reconciled with the alpha-iron hypothesis of martensite formation called the "epsilon-eta hypothesis." They conclude from their investigations that when austenite changes to martensite in quenched steel there is a change in the carbon content of the austenite and the martensite. They claim that besides austenite and ordinary ferrite, two formations, epsilon and eta, are found in quenched steel, and that these two are in metastable equilibrium with the austenite. The martensite contains less carbon than the austenite, with which it is in contact. A constitutional diagram showing the lines of the metastable martensite system is given. According to the authors' hypothesis of the martensite system there is a transformation in pure iron at a certain temperature. By experiments this temperature was found to be 685 deg. cent. In performing these experiments small pieces of soft Krupp iron containing 0.07 per cent carbon were used, and an electrocardiograph used for recording the thermal changes. A description of 71 photomicrographs is included.

It is important to remember, however, that the constitutional diagram given in the above paper in showing a metastable martensite system applies only to iron-carbon alloys which are low in manganese. The relative positions of the cementite and martensitic system might be shifted in special steels.

Practical Applications of the Knowledge of Crystalline Structure of Metals

At first glance it would appear as if the subject of crystalline structure of metals had merely a theoretical interest. After all, it simply shows the distribution of atoms and molecules in a metal, and one might question the utility of such knowledge to the practical engineer, presumably more interested in what the metals with which he has to deal are than in the underlying reasons why these metals are what they are. Actually, however, it is not so, for knowledge regarding the crystalline structure of metals throws a vivid light on a number of phenomena with which the engineer has to deal. It explains, for example, the reasons for the toughness and brittleness of certain metals and alloys, the phenomena of hardening, the whole subject of strength of metals, and the true meaning of the conception of solid solutions without which the metallurgy of steel cannot be properly understood. We shall start with this latter.

Solid Solutions

In the first chapter, on the Physico-Chemical Properties of Metals, it was shown how steel from the liquid state passed to that of austenite, which is a "solid solution" of carbide of iron in gamma iron, and an example was given to illustrate the meaning

of the term "solid solution." An engineer, however, while knowing in a general manner that solid solutions exist, cannot well realize as a rule just how such a thing is possible. The mechanism of solutions in liquids is fairly obvious. If we drop a lump of sugar into a cup of hot tea, we can at times see how the water tears away particles of sugar, breaking them up into minute particles, and it is easy to understand how gradually, especially when the liquid is agitated, the sugar spreads through the whole cup. When we deal, however, with solid solutions, the conditions seem to be such as to oppose the operation of the process of solution. Here we are dealing with solids such as carbide of iron and gamma iron, and it does not appear at all clear how interpenetration and relative movement of particles of the two solid substances can take place to an extent necessary to produce the intimate phenomenon known as solution. In other words, it is not clear to those who have not studied the crystalline structure of metals how the diffusion between metals can occur. This is, however, quite well explained when we remember that each crystal cell of the metal consists of several atoms located symmetrically with respect to some central point at not inconsiderable distances from each other, with an additional atom in the center of the crystal or on its face.

Starting with this the British metallurgist, Dr. Walter Rosenhain, put forward a theory to explain diffusion between metals. What he claims is, that where solid solution occurs, an atom or atoms of the solvent displace corresponding atoms of the solute, the "stranger" atom being forced to take the place formerly occupied by a "host" atom and to behave in exactly the manner of its host. As a rule, the stranger atoms have dimensions different from those of the host atoms which they displace, and the substitution of a larger or smaller atom in the crystal structure sets up intense local forces in the immediate neighborhood of the stranger atoms that cause slight slips, which are probably of only a few atom diameters. Only a row or single line of atoms may move, but this movement would be sufficient to account completely for diffusion.

In this case one metal is actually the solvent and the other the solute, the former, which is the predominant metal, preserving its correct spaced lattice, while the solute appears in the form of individual atoms replacing certain atoms in the lattice of the solvent. With the gradual increase of the solute a time comes when the latter becomes the predominant metal, in which case the roles are reversed. If the crystal structures of the two metals are alike, there is an unbroken series of solid solutions, the positions of the atoms changing continuously with corresponding changes in the interrelation between the atoms of the two metals in the lattice. If the metal B has a different crystal structure from A, the new structure makes its appearance towards the B end of the series, atoms of A replacing B atoms in the crystal lattice of the latter.[13,14]

It has been noted in Chapter I that when steel passes through certain critical points a change occurs in the volume simultaneously or nearly simultaneously with the "kink" in the temperature-time curve. It was generally stated that both the evolution and absorption of heat, which keep the temperature of the metal steady for a while after it has been either gaining it or losing it, and the change in volume were due to changes in the structure of the metal. We can see now from our knowledge of the crystalline structure just what these changes are. If iron is heated through the upper critical range the former sorbitic, troostitic, and martensitic structures pass into austenite, which is a solid solution. This means that the molecules of carbide of iron shoulder their way into the neighboring gamma-iron lattices; the situation being practically as if a grown-up person came to a table occupied by children and after pushing one of them out of the way, sat down to the meal. The invader molecule being of different size, produces a change in the volume of the resultant material (solid solution). Not only that, but it takes a certain amount of energy for the stranger molecule to force its way into the original space lattice, as the host atom, so unceremoniously shouldered out of the way by the stranger, does not yield his place without certain opposition. The energy thus absorbed is shown negatively on the pyrometer by the fact that the rise of temperature is suspended for a while notwithstanding the fact that heat is being added the whole time. When the metal is being cooled through the critical range the contrary phenomenon takes place and the fall of temperature stops for a while, notwithstanding the fact that heat is being lost from the metal. This would indicate an internal evolution of heat produced by expelling the stranger molecules and reconstructing the original lattice. On the other hand, however, A. Westgren and G. Phragmen[11] claim that austenite is not formed by simple substitution of metal atoms by carbon atoms, but represents an additive product with the carbon atoms situated in the interstices between the metal atoms.

The Structure of Actual Metals

Such figures as Figs. 18, 19, and 20 show the structure of what might be called an "ideal crystal," such as would be formed provided there were no interferences with its formation on the part of other crystals. This happens when a single crystal is allowed to develop from a molten bath. Actually, however, in the vast majority of cases a somewhat different process takes place. As the metal cools, nuclei form at various spots throughout the molten mass. These nuclei or minute crystals grow in size with the loss of heat. As a rule this growth does not take place simply by the accretion of concentric layers, but by the crystal's acting in the manner of an octopus and throwing out a number of arms into the surrounding liquid, these arms in their turn sprouting feelers,

and the final structure somewhat resembling a bush. (This is one of the reasons why such formations are called "dendrites," from the Greek word *dendron*, meaning a tree or bush.) Since, however, these formations are initiated simultaneously at a number of points throughout the liquid mass, sooner or later the branches of the various dendrites encounter each other and a fight for room begins, the mutual pressure of the branches preventing them from retaining the ideal crystal form. The result is a system of crystals with an orderly arrangement of the atoms in the interior but an external shape determined by the influence of other crystals. Such crystals are called "crystallites" or "grains." No two adjacent grains in the cast metal have the same orientation, that is, the same direction of the crystallographic axes. If they had the same orientation, the two grains would become one. A metal, therefore, which has solidified from the molten state consists of an aggregate of differently oriented grains, somewhat like the structure diagrammatically shown in Fig. 22, taken, through the courtesy of D. Van Nostrand Co., Publishers, from An Introduction to the Study of Physical Metallurgy, by Walter Rosenhain, 2nd edition, 1923 (Fig. 14e, Plate IV).

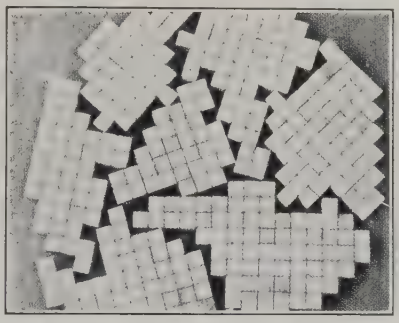

FIG. 22 DIAGRAMMATIC ILLUSTRATION OF THE DISTRIBUTION OF CRYSTALS AND INTERCRYSTALLINE MATERIAL

(Fig. 14 of an Introduction to the Study of Physical Metallurgy, by Dr. Walter Rosenhain, Reproduced by courtesy of the publishers, D. Van Nostrand Company, New York City.)

While it is generally assumed that crystallization is a continuous process, Col. N. T. Belaiew,[4] from observation on the Tschernoff crystal (a steel crystal about 15 in. long which was found in the upper portion of the pipe in the sink head of a soft-steel open-hearth ingot weighing something like 100 tons), comes to the conclusion that crystallization may proceed not continuously but by pulsations or leaps, and advances the proposition that perhaps that is a general occurrence.

The question now arises, What is the structure of the black spaces between the grains in Fig. 22? The origin of these spaces is obvious. The grain formation proceeds until all the liquid metal that can go into grains is exhausted. When this happens, and possibly when some other factors come into play, grain formation stops. The original idea was that there were voids between the grains, but this hypothesis has been abandoned, and the theory which is more and more receiving acceptance today is that the

spaces between the grains are filled by an amorphous material acting as an intercrystalline cement.

Before we proceed to the discussion of this latter, it may be mentioned that the above discussion of the method of growth of dendrites explains the difference in structure between chilled castings and slowly cooled castings. (An interesting example in the difference of structure of the two may be found in photomicrographs shown by Paul Oberhoffer.[7]) It is generally known that chilled metals are fine-grained, while slowly cooled metals are coarse-grained. This is obviously due to the fact that in chilled metals the temperature drops so rapidly that an enormous number of nuclei are formed, and the dendrites are developed at so many points that there is but little room for them to grow. In slowly cooled metals the number of dendrites is comparatively small, and enough time and material are available to permit each nucleus to appropriate a comparatively large amount of liquid metal for its growth, which results in a large and coarse-grained structure.

The Amorphous-Metal Hypothesis

The term "amorphous" is in the main sense the direct opposite of "crystalline" and defines materials whose molecules do not possess such a regularity of arrangement as characterizes crystalline materials. In application to metals Beilby[3] used the qualifying adjective "vitreous," applying it specifically to substances which in some degree resemble the glasslike form assumed by the silicates when they are solidified from the molten state. Amorphous solids are essentially undercooled liquids of great viscosity. The constitution of the liquid is preserved, and with it the property of fluidity masked from casual observation by the high viscosity. (Jeffries and Archer, p. 64.) Glass may be taken as an example. On cooling from the molten state it passes in a continuous manner from a liquid which can readily be poured, to the solid commonly known at ordinary temperatures and which has a hardness comparable to that of the hardest steel. In spite of this hardness, a rod of glass supported at the ends will sag or "flow" under its own weight in the course of months or years.

Beilby has shown that amorphous metal is produced in the operation of polishing or rubbing done at room temperature. Such rubbing, however, can be produced not only by polishing the surface but by rubbing the crystals themselves over each other, or by block movements of crystals along certain crystallographic planes known as "gliding" planes or "slip" planes. This takes place, for example, in the cold drawing or cold rolling of metals. Such cold working results, according to Beilby, in the formation of amorphous metal films at the planes of rubbing, and produces hardening as layers of cementing material of a vitreous, amorphous character are formed at all surfaces of slip or shear throughout the mass. There is a limit to the amount of cold deformation that a

metal will stand, and further attempts cause rupture. According to Beilby, the fact that overdrawing reduces the strength is due to the exhaustion of available crystalline material, and he regards the crystal modification of the metal as the sole source of plasticity. When the available supply of crystals is exhausted the metal becomes essentially glasslike in structure, and, like glass, incapable of further deformation.

The effect of cold rolling on sheet steel was investigated by Y. Niwa and J. Matura,[15] who found that in cold rolling the strain penetrates gradually from the surface of the metal into the interior, and that the crystal grains are broken up into smaller cubic aggregations which tend to arrange themselves so that one edge of the cubic lattice or one diagonal of the face is parallel to the direction of rolling.

Metals which have been hardened by cold work are softened by heating to a suitable temperature. The softening is accompanied by the restoration of ductility and by the substitution of a clearly crystalline structure of "equiaxed" grains (i.e., grains whose diameters are approximately the same in all directions) for the disordered structure found after cold working. This operation is called "annealing," and is a regular part of most industrial processes involving the cold deformation of metals. The softening is explained by Beilby's theory as due to the recrystallization of the amorphous metal produced by the cold work. Disappearance of the amorphous metal would, of course, involve the simultaneous disappearance of the hardness and brittleness supposed to be due to it. This would explain why in such operations as cold drawing it is necessary to anneal metal between passes. The amorphous-metal hypothesis is, however, by no means universally accepted, and some metallurgists assert that in cold work and polishing metals are fragmented, and not amorphized.[16]

Intercrystalline Cement

From what has been said above, it would appear that metal such as iron or steel consists of a jumble of grains, of which no two lying side by side are oriented in the same direction, with the irregular spaces between the grains (the black spots in Fig. 22) filled with an amorphous material. The remarkable part about this is that when pure metals at room temperature are broken, the fracture passes almost exclusively through the grains rather than between them, from which it would appear that the grains are weaker than the boundary material. When, however, metals are broken at temperature closely approaching their melting points, fracture follows the intergrain spaces rather than the grains themselves. Furthermore, permanent deformation of metals consists of plastic deformation of the crystalline grains by the process of slip. In the case of ductile metals, fracture through the grains is necessarily preceded by some plastic deformation of the grains and

a general deformation of the metal as a whole, so that when the fracture takes place through the grain it is accompanied by a ductile break. All of these and some other facts lead to the belief that the grains of metals are held together by a cement of a vitreous, amorphous nature. This cement is hard and strong at the lower temperatures, stronger in fact than the grains. As the temperature rises the amorphous cement softens, and Bengough[5] has expressed the opinion that it disappears entirely at high temperatures, where the grains readily pull apart without any appreciable deformation.

Of late two factors have come to light which apparently support this theory. One is the result of an investigation by Dr. A. P. Davey in which it was found that single large grains of copper have a materially higher electrical conductivity than the purest copper wire (the electrical conductivity of granular is usually higher than that of amorphous materials). The other fact which may have a bearing on the same subject is the remarkable ability of high-chromium metals to retain their strength and especially hardness at high temperatures where ordinary steel is comparatively weak.

Beilby has also advanced the theory of hardening by the formation of amorphous metal, and Rosenhain expresses the belief that the great hardness of hardened steel is due to the presence of an extremely minute network of amorphous layers surrounding the very fine grains of alpha iron which result from the rapid transformation of gamma iron. This would explain why two such apparently opposite operations as cold working on the one hand and quenching of hot metal in water or oil on the other, produce apparently similar results, and why annealing in both cases relieves the metal of its hardness.

Recrystallization[11]

It has been stated above that severe cold working produces hardness in metals and that subsequent annealing removes this hardness. Further investigation has indicated that each metal has a temperature at which the grain structure distorted by cold working is replaced by new grains usually of approximately equiaxed shape (by "equiaxed shape" is meant one whose diameter is approximately the same in all directions). The change produced by heating to or above this temperature (which for iron is a minimum of 450 deg. cent.) when the strain-hardening effect is lost, is called "recrystallization." It is not intended to go into a full discussion of this subject here, and the reader is referred for further information to Chapter 5 of Jeffries and Archer's Science of Metals, from which the following paragraph, however, is taken.

Iron is unique in its grain-growth characteristics because of the allotropic change in a temperature region permitting grain growth. If iron is cast, it forms grains of gamma iron above 900 deg. cent., crystallizing with a face-centered cubic lattice. On cooling, gamma iron changes completely

into a body-centered lattice at about 900 deg. cent., and this transformation gives rise to entirely new grains. If the iron is kept below 900 deg. cent., it behaves much like any other metal within a similar temperature range. It can be cold-worked and hot-worked, and the grain-growth characteristics can be studied at temperatures up to 900 deg. cent. On heating above (about) 900 deg. cent., however, the structure again changes completely into new grains of gamma iron. Every time iron is caused to change from one crystal lattice to the other a new set of grains is produced. Pure gamma iron cannot be cold-worked, because at the lowest temperatures at which it is stable it cannot be strain-hardened.

It has been found also that the greater the degree of strain hardening, the lower will be the temperature of recrystallization. The recrystallization temperature, however, not only varies for different treatments for different pieces of the same metal, but it varies within the same piece of metal if a homogeneous condition does not exist. With mild cold deformation and large grains it is impossible to produce a condition even approximating homogeneity, and such samples usually recrystallize over a considerable range of temperature. The greater the amount of strain hardening, the smaller this range will be, i.e., the complete change in structure from strained to unstrained grains will take place within a smaller temperature range. Furthermore, the lower the recrystallization temperature, the smaller the grain size, which explains why overheating steel causes what is known as a "coarse" grain.

Crystalline Structure of Metals, Their Strength and Hardness

It has been shown above that metals such as iron consist essentially of crystals having, when not deformed by their own interaction or outside agencies, the shape of cubes with atoms located in the corners and additional atoms in the center of the body or the center of each of the faces of the cubes, and while the distance between these atoms has to be measured in Ångstrom units, each of which is roughly one-two hundred and fifty millionth part of an inch, these distances are quite large as compared with the size of the atom itself. Furthermore, these distances are not accidental but are due to the action of forces holding the atoms together, and the atoms vigorously oppose every effort to change the interatomic distances within the crystal or the distances between the crystals. If an attempt is made to bring the atoms closer, as, for example, by applying compressive stresses to a metal, the repulsive forces between the atoms come into play and the amount of force necessary to overcome them expresses the compressive load. When an effort is made to pull a metal apart, the cohesive stresses oppose it.

It may be of interest in a general manner to see just what factors affect the character of the crystal and grain structure of metals. As has been already stated, rapid cooling from the liquid state tends to result in a fine grain structure, and slow cooling in extended dendrites and coarse grains. It has been observed, also, that the presence of impurities at times in very small quantities

may affect the crystalline structure of iron. This may explain why the addition of such a small amount as 0.1 per cent of vanadium or molybdenum has so great an effect on the mechanical properties of steel and markedly increases the ability of the metal to resist alternating stresses. Attention has also been called to the fact that cold working followed by heating to a proper temperature produces a refinement and rearrangement of the grains. In a way hot working is equivalent to cold working and heating, with the distinction, however, that the working and heating are simultaneous instead of the heating following the working. It produces a refinement of the grain essentially in the same manner as heating after cold working, but also produces a tendency for the grains to rearrange themselves in the direction of working. This may be called a "pseudo-fibrous" condition of metal.

The hardness of solid solutions is due, according to Rosenhain, to distortion of the normal space lattice of one of the metals by the substitution of atoms of the other metal for its own atoms, this distortion serving as a hindrance to slip on the crystal planes. The more soluble in each other two metals are, the less distortion is produced; the less soluble, the more distortion and hence hardness of the resulting product. This explains why gold and silver alloys are soft (the two metals being soluble in all proportions), while carbon, being but slightly soluble in gamma iron, produces a hard material.

Jeffries and Archer have ascribed hardness of metals to what they call "slip interference," which means the presence of a structural condition which interferes with slip along the cleavage planes of the crystals of the metal. In a pure metal this would be produced by grain refinement, in cold-worked metal, by the fragmentation of the grains; while the slip within the grains is opposed by the presence of a hard constituent uniformly distributed, the effect of the hard constituent depending on its amount and, within certain limits, the fineness of its subdivision.

Plastic Strain in Metals

According to H. J. Gough,[8] the mechanism of plastic strain in metals is a process of slip on crystallographic planes. He bases this conclusion on the result of the work of Taylor and Elam.[9] The measurements carried out by these investigators on a single crystal of aluminum showed that for extensions up to and including 40 per cent, distortion occurred by a process of slip or shearing on one set of octahedral planes; further, the direction of the slip was along one of the three principal lines of atoms in this octahedral plane. At 40 per cent extension of the specimen a second set of octahedral planes assumed the same inclination to the axis of the specimen as that set of planes on which slip was taking place. Subsequent distortion occurred by simultaneous slip on both sets of planes. It was also brought out in this research that although the origin of the crystal axes with respect to the axis of the speci-

men was changing during the earlier stages of the tests, yet the crystalline symmetry was preserved at all stages of the test. In other words, measurement of the dihedral angles contained by the crystallographic planes showed that even in the last stages of distortion the specimen remained a single crystal.

It may be asked why the process of slip once started, due to the application of load, is arrested before fracture occurs. An explanation has been offered that slip in a body-centered cubic atomic arrangement is arrested by a transition to the hexagonal close-packed system which possesses only one set of planes along which easy gliding can occur. On the whole, as between Beilby and Rosenhain and their followers, two theories exist of the mechanism of plastic strain of a crystalline substance. First, that when the limiting elastic strain of the space lattice has been exceeded, gliding motion occurs by a process of slip along atomic planes; the amount of relative movement between two adjacent planes being a multiple of the interatomic distance, hence when such movement has ceased, the lattice distances and angles remain as before movement took place. Secondly, the amorphous theory requires that on the surface of the slip planes on which gliding has occurred the crystalline structure shall be completely broken down, resulting in the formation of non-crystalline material on these planes. A third theory was recently proposed to the effect that the mechanism of plastic flow, although at first characterized by the tendency to form gliding planes, nevertheless proceeds during the major portion of the flow period without any recognizable formation of these gliding planes. During this latter period the space lattice can be entirely destroyed, both lattice distances and lattice angles being permanently distorted.

The foregoing brief discussion of the relation between the plastic flow in metals and the crystalline structure of the latter has been introduced here largely to show what a vivid light the study of the atomic structure of metals can throw on such matters of interest to the mechanical engineer as the theory of elasticity and strength of metals. It should be remembered in this connection that the whole subject of investigating the crystalline structure of metals is extremely young—in fact, barely ten years old—and if so much information has already been obtained in that brief period it is easy to see how much more may be expected from this new method of investigation when its proper technique and the necessary apparatus have been developed.

Widmanstaetten Figures

What is known as "primary crystallization" occurs within the range of temperatures between the points A and E of the constitutional diagram of the iron-carbon system given on page 24, or between 1500 and about 1150 deg. cent. This crystallization leads to the formation of crystallites which are subsequently con-

verted into dendrites. At lower temperatures what is known as "secondary crystallization" may take place. One of the forms resulting from this secondary crystallization is known as "Widmanstaetten figures." They occur if the interval range of secondary crystallization which lies between the point *G* or 900 deg. and some point below the line *PSQ* but near it, is covered too rapidly. A certain amount of the proeutectoid element separates then more or less instantaneously throughout every grain, this separation following the crystallographic planes of the octahedron.

Such a structure was first observed in 1808 on the meteorite, known as Agram Iron, by Alois Widmanstaetten (at that time director of the Imperial Porcelain Works at Vienna). Later on, somewhat similar structures were found here and there in ingots, and finally Col. N. T. Belaiew[5] produced an alloy in which the meteoric structure was artificially duplicated. Carl Benedicks[6] conceived the idea of suppressing the possible dendritic crystallization by first rapidly cooling from the melt (from about 3000 deg.), then bringing it again in the gamma zone (a possible granulation zone), and finally letting the alloy cool as slowly as possible through the area of secondary crystallization and the eutectoid zone.

His insight was rewarded by a brilliant success, as in his second melt he was able to obtain a large amount of iron-nickel constituents of the type found in meteorites, as well as a fine and distinct Widmanstaetten structure.

The following significant conclusion is drawn from this investigation by Belaiew: "The structure of meteoric irons is no more a mystery to us, but in solving that mystery the meteorites seemed to bring to us a message causing us to know and understand that the same laws govern the synthesis and crystallization of matter both here on our earth, and there in the vast infinite space whence the meteorites come."

How the Crystalline Structure of Metals Was Determined

It may be of interest to state briefly how all this knowledge about the crystal structure of metals has been collected. It is comparatively simple to investigate the crystalline structure of such materials as rock salt, because they are transparent, but iron is not. Some means had to be found to "see" the structure of the metal, and these means were found as a by-product of a truly theoretical investigation which at first did not promise to be of any interest to the metallurgist.

Some years ago a good deal of doubt was felt as to the true nature of X-rays, namely, whether they were corpuscles traveling at immensely high speeds or waves similar to light waves. In the case of ordinary light this question is determined by measuring the wave of light by means of a diffraction grating, but the X-ray wave is extremely short—from 1000 to 50,000 times shorter than the shortest light wave—and a diffraction grating to permit the

measurement of even the largest X-ray wave would have to have some 20,000,000 lines to the inch. It is obviously impossible to make such a grating, even by the finest ruling machines that we know of.

Under these conditions Dr. von Laue had the brilliant idea of employing a natural crystal as a diffraction grating, his assumption, which he first developed mathematically, being that the atoms in a crystal ought to be regularly arranged, and that if a number of crystal units such as are present in an ordinary crystallite were taken, a sort of grating would be formed by the interatomic spacings throughout the crystal. While the method employed by Laue proved to be cumbrous, it confirmed his assumption and permitted measuring the lengths of waves constituting X-rays, incidentally proving that the only essential difference between visible light and X-rays is the length of their respective waves.

When the length of waves of X-rays of various kinds became known, several attempts were made, with ultimate success, to apply X-rays to the determination of the structure of various crystals. This was done by Sir W. H. Bragg and W. L. Bragg in England, Scherer and Debye in Germany, and Albert B. Hull and A. P. Davey in this country, Hull having also developed a modification of the Laue-Bragg process known as the "powder method" of crystal analysis. (For a brief description of the powder method, compare p. 67 and Jeffries and Archer, pp. 55–57.)

One of the remarkable features of the application of X-ray analysis and its modification to the investigation of crystalline structure of metals is the high precision of the results obtained. It has recently been stated by Dr. Walter Rosenhain in a lecture before the Society of Arts (February 16, 1925) in London, that the distances between the atoms in a great many crystalline substances are known to within an accuracy of much less than one-half of the one per cent. To understand the full significance of this statement, one has to realize that these measurements are effected in Ångstrom units, each of which is one-ten millionth part of a millimeter, or about one-two hundred and fifty millionth part of an inch.

Quite recently the General Electric Company, using an idea proposed by a German scientist, Dr. H. Barkhausen, developed a little device by means of which the noise produced by the movement of atoms when a rearrangement therein takes place can be plainly heard. This device consists of a cascade vacuum-tube amplifier of essentially the same design as used on some of the radio receiver outfits, connected to a pick-up coil having 17,000 turns. When an iron bar is inserted into this coil through which the current is flowing it becomes magnetized and this produces some kind of a shifting of the atoms, which is heard in the head phones of the amplifier as a roar. If the bar is rapidly withdrawn from the coil and reinserted, only a slight amount of the magnetization is lost, and accordingly when the bar is reinserted, instead of a roar there is only a slight noise. The device operates, of course,

on a principle entirely different from another device (the "clink" detector for discovering fissures in forgings) which will be described in a later chapter.

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CHAPTER III

DETERMINATION OF THE PROPERTIES OF METALS

It is important for the mechanical engineer to understand how the properties of metals are determined. To do this numerous tests have been developed, but with the exception of some very unusual cases, it is by no means necessary to put a metal through all the tests that are to be described. Thus, there will be no sense in testing a rail for resistance to stresses at high temperatures, because a rail in service is not exposed to high temperatures.

The tests to which metals are subjected may be divided into the following classes: Physical tests; chemical analysis; determination of structure by microscope, reflection photography, and X-ray photography; magnetic analysis; analysis by sound; determination of corrosion resistance; determination of erosion resistance; determination of electrical properties; spectroscopic analysis; determination of physical constants; tests for machinability, cold and hot working, and forging; determination for stability, physically and chemically.

Physical Tests

Some of these are so familiar to mechanical engineers that they need be mentioned by name only; concerning others a few words may be added. Tensile tests, compression tests, bending tests, impact tests on plain and notched specimens, and alternating-stress tests in metallurgical work do not differ in any way from those used in mechanical engineering, except that, especially of late, metals have been tested for their physical properties not only at room temperature but also at temperatures ranging as high as 2200 deg. fahr.[16]

As regards hardness, it is important to understand that the various tests such as the scratch, Brinell, Shore, Rockwell, and Herbert do not all indicate the same property of the material. As has been already stated in a paper published in *Mechanical Engineering*,[11] "It would appear that there are five distinct kinds of hardness, of which two are complex and three simple: (1) *Compound indentation hardness*, measured by the pendulum time test, a composite quality comprising (*a*) *plastic indentation hardness*, measured by the Brinell test, and (*b*) *elastic indentation hardness*, measured by the pendulum time test on glass, rubber, and the hardest steels, but otherwise not yet isolated; and (2) *work hardness*, or resistance to working with a tool, measured by the pendulum scale test, a composite quality comprising *hardness indentation* as above and *flow hardness*, or resistance to flow, measured by the pendulum scale time ratio."

Furthermore, in special reference to plastic indentation hardness,

the Brinell test, which uses a ball, indicates the *average* hardness over a comparatively extensive area. The Rockwell test with its small diamond point is capable of measuring hardness over a very much smaller area, often equivalent to that of one crystallite or even a part of a crystallite and is thus capable of giving a reading more representative of the actual conditions than the Brinell reading integrated over a much larger area.

It has been found that alternating-stress tests are apt to give misleading results unless certain precautions are taken to obtain a correct application of load. This has been done, among other methods, by inserting a thin cardboard cylinder between the test piece and the inner race of the ball bearing through which the load is transmitted, the purpose of the cardboard cylinder being to assist in uniformly distributing the load.

While there is undoubtedly a close relation between the physical properties of metals and their constitution, it has not been sufficiently established so that one can be guided by any definite rule. Generally brittleness increases, other conditions being constant, with the size of the grain, but it is possible for an alloy consisting of small grains to be more fragile than one consisting of larger grains, given a certain orientation of the grains (cp. Chapter II on Crystalline Structure of Metals). It is also possible, to a certain extent, to predict the mechanical properties of metals from their constituents, but here also our knowledge has not yet reached the stage where such predictions can be relied upon for practical purposes, so that the test is the final determination of the mechanical properties of a metal.

It is important to remember that the results of all tests depend on the extent to which the piece tested is representative of the material the qualities of which it is desired to know. Thus, for example, when a casting is made and a test bar cast from the same metal and the latter on test shows excellent properties, this does not mean that the casting will stand up well in service, because the pattern may have been so improperly designed as to produce thin sections between heavy sections, with the result that contraction stresses will bring about the rupture of the former. A good deal depends also on the type of test bar and method of casting it. For certain cases such organizations as The American Society for Testing Materials have adopted rules as to the methods of casting standard test bars. Where such rules have not been adopted an endeavor should be made to have the test bar cast in substantially the same manner as the casting, and, for example, such practice should be avoided as having the test bar cast in a metal mold where the actual casting is poured in green sand.

Chemical Analysis

The purpose of the chemical analysis is to determine whether certain useful constituents are present in sufficient quantities and

certain undesirable elements are kept below the specified limit. The important constituents in ordinary steel are carbon, which, as has been stated above, vitally determines all the properties of the metal; sulphur and phosphorus, which often give it undesirable properties; and silicon and manganese, the influence of which will be discussed later, and which may be considered desirable or harmful within certain limits and less so within other limits. In alloy steels the alloying elements must be present within certain limits, and it is up to the analysis to establish it. It is well to state in this connection that on the whole it is not desirable to specify both the chemical analysis and the physical properties of a metal.

It is often impossible, especially on account of the practice followed in a given foundry or steel mill, to produce a metal of a certain chemical analysis which at the same time will have certain physical properties. Therefore, if it is the analysis which is important, only that should be specified, and in some way proper inspection should be provided to see that metal of the desired analysis is melted and handled properly. If it is the physical properties which are desired, they should be specified and a certain leeway given in the matter of the analysis to permit the foundry or steel mill to use its own judgment in producing a metal endowed with these properties. To specify both is like telling a man to take only so many steps per minute and yet cover a certain distance in an hour. This would be all right if all men had legs of the same length and their steps were of the same spacing. As a matter of fact, steels made from Swedish ore and Ruhr coke, for some reason or other, have physical properties (with the same treatment) not at all like those made from Mesabi ores and Connellsville coke and apparently of the same composition.

In specifying the analysis of a steel, it is important to determine first of all the purpose for which the metal is to be used and the processes by which it is to be manufactured. For example, in steel used for rolling structural shapes, a small amount of oxidation, provided it does not result in what is known as "dirty" steel, is fairly harmless. If, however, the steel is to be case-hardened, the same amount of oxidation may prove to be very objectionable.

This example, it may be noted, is of interest in that it shows how at times the problem of analysis is handled by the steel man. The usual way is of course by direct determination. Once in a while conditions arise, however, when roundabout ways appear to be more effective. Such, for example, is the case of steel for roller-bearing races. This steel has to be case-hardened, and the presence of oxides in the metal would interfere with the case-hardening. Now while it may be possible to discover the presence of oxides in steel by means of chemical analysis, there is no rapid method of analysis available. Because of this, the Timken Roller Bearing Company uses a somewhat roundabout method and specifies 0.5 per cent chromium in its steel, the idea being that if oxides of iron were

present in the steel there would not be any chromium in it, as the latter metal oxidizes long before iron does. Here, therefore, by determining the amount of chromium present, a conclusion is reached as to the presence, or rather the absence, of oxides of iron. In other instances, however, the practice of using deoxidizers or indicators is objectionable and therefore prohibited. Thus rail specifications usually provide that no aluminum shall be used as a deoxidizer, because of the fear that heavily oxidized metal would be produced in the furnace and that reliance would be placed for its deoxidation on the use of aluminum, a process not really sufficiently certain to be relied upon in the case of a product, such as rails, where reliability and safety are paramount (cp. also p. 11).

As regards phosphorus, there is fair agreement that it should be kept below 0.05 per cent, and even lower limits are specified where articles are subjected to heavy alternating stresses and the danger of cold-shortness is particularly prominent. On the other hand there is much less unanimity as regards the upper limit for sulphur. Some ten years ago 0.05 per cent was considered the highest limit permissible for all products subject to stresses. Of late, however, a closer study of the influence of sulphur has been made and there have been apparently well supported claims that higher limits of sulphur may be permissible under certain conditions. According to tests by J. R. Cain,[13] if sulphur is below 0.01 per cent there is no red shortness, even with a comparatively high oxygen content (0.2 per cent). If the sulphur is above 0.01 per cent, a manganese sulphur ratio of three to one is sufficient to prevent red shortness.

As a rule, no single set of tests will tell the whole story. Thus excessive brittleness as discovered by the impact test or alternating-stress test may be due to an accidental defect in the test piece, such as a bit of slag inclusion, of which the article itself may be free. A sulphur content in excess of the supposed permissible higher limit may under certain conditions prove to be beneficial rather than harmful, but when excessive brittleness is found in combination with excessive sulphur content (this is, however, cited merely as an illustration), it is well to consider immediately whether lowering the sulphur limit would not prove to be of advantage. On the other hand, when unusually high physical properties are discovered with an apparently conventional analysis, it may be well to subject the test piece, especially if made from materials of unusual occurrence, to a complete analysis, that is, an analysis that will show constituents totaling 100 per cent, in order to discover if there is not some constituent present that would account for the unusually excellent properties.

It is well to understand that in the first place chemical analysis of the metal does not always disclose all that goes into the making of the metal or all that affects its properties, and second, that unless

one knows what to look for in a chemical analysis it is very easy to fail to discover certain constituents even when present. This is due, first, to the fact that certain alloying elements affect the structure of steel while present in molten metal, and then pass into slag so that they are not present in the cast metal. Such an element is titanium, titanium steel so-called—and quite legitimately—often showing no presence of titanium on chemical analysis. Other alloying elements are added in such minute quantities that they would not be discovered by ordinary analysis unless their presence was suspected and certain reagents used. Such an element is vanadium, which is added in quantities of only 0.1 per cent, and the magnesium or cerium used as a deoxidizer in some special steels is added likewise in quantities of 0.1 per cent or less. These deoxidizers pass into the slag so completely that their presence is not discoverable in the cast metal. Of late an attempt has been made to introduce certain organic materials into molten steel, and it is claimed that the resulting metal is improved thereby. Of course, such organic materials would undergo under the action of heat at the temperatures of molten steel such a thorough transformation as to make their presence absolutely undiscoverable in the final metal.

The methods of making the analyses themselves do not differ from those commonly employed in inorganic chemistry, except that metallurgical chemists have developed certain rapid methods of determination not always familiar to the general chemist.

The ordinary chemical specification covers only the solid elements contained in steel. There is, however, increasing evidence that the presence of gaseous elements, such as nitrogen and hydrogen, materially affects the properties of metals, thus lending support to the contention of some British crucible-steel melters of the early part of the 19th century that they could judge of the character of a steel by the smell of a fresh fracture (the smell possibly resulting from a very faint evolution of hydrogen sulphide). There are (still somewhat uncertain) methods for determining the nitrogen and hydrogen entrapped or dissolved in steel, but none applicable in shop practice, and hence no insertion of any specification in the chemical analysis as to occluded or dissolved gases in steel would be acceptable to a steel mill. Furthermore, what is known in regard to the influence of gases in steel is as yet too fragmentary to be of real practical value. At times it may be also of interest to determine the character of the so-called "sonims" or solid non-metallic inclusions in steel or iron.

Determination of the Structure of Steel and Iron by Microscopy and Reflection Photography

As stated in many instances in the preceding chapters, the two main constituents of steel, carbon, and iron, and some of the alloying elements combine with each other in many ways within the same quantitative relation. Thus, it may happen that two ma-

terials showing the same chemical analysis will prove to be widely different from each other. As an instance of this may be cited white iron and malleable iron, pearlitic and martensitic or pearlitic and sorbitic steels, etc. In fact, the structure of ferrous materials has far more influence on their industrial properties than their analysis, as it is the structure of these materials which primarily defines their ability to resist the various chemical, physical, and thermal stresses to which they are subjected in the course of the performance of their various tasks. It becomes of very great importance, therefore, to find a method that will permit of an insight into their structure, which in this case means the size of the grains and their location with respect to each other, the compounds in which the iron, carbon, and other elements occur in the metal, and the uniformity or lack of uniformity of the structure throughout the various sections of a given body of metal. It is also important to discover whether or not there are planes of weakness in the metal or minute inclosures of foreign substances that might become starting points of possible future cracks. None of these factors can be discovered as far as we know by means of either physical tests or chemical analysis, but the microscope offers a powerful tool for the investigation of these phenomena, especially when combined with various photographic methods. Of these latter there are two classes, one using visible light as an illuminant, and the other using X-rays. In order to avoid confusion between the two, the former will be called here "reflection" photography, as it operates by rays reflected from the object to be photographed on the sensitive plate or film, and the other "X-ray" photography, as it is effected by rays penetrating *through* the object photographed to a sensitive plate or film on the side of the object opposite to that where the source of the rays is located.

As regards the microscope, which includes the common magnifying glass, there are two ways of applying it: one to a fracture, especially a fresh one, of a metal, and the other to a specially prepared surface. The former, except in some unusual cases, gives only a rough idea as to the structure of a metal, but may be of considerable use in helping to discover local flaws which led to fracture, such as slag inclusions, blowholes, cavities, previously unknown surface defects, etc. The great importance of microscopic, photomicroscopic, and direct photographic examination is due, however, to the information obtained by the investigation of specially prepared surfaces.

In order to obtain a view of the structure of a metal under the microscope, it is necessary to prepare what is known as a "microsection," which means that the surface of the metal should be polished free from scratches and chemically treated (etched in a certain manner so as to bring out the various constituents of the metal).

The first operation is usually that of sawing off a piece of suitable

size, which may be done with a hacksaw or thin grinding wheel. Either method will give a surface of irregular texture and more or less deeply scratched. The next operation is therefore to remove the deep scratches, which can be done on an ordinary bench grinder with emery or carborundum wheels. It is often necessary to perform this operation with a stream of water playing on the piece to prevent it from heating. The coarse grinding is followed by fine grinding, an operation which requires a good deal of skill to be performed properly. The operation known as burnishing cannot be used in the preparation of microsections, because although it does produce a very smooth-looking surface, this surface is obtained by a sort of smearing over of metal in a surface layer which disappears on etching and leaves below an irregular surface. After the specimen has been ground on the finest emery paper (No. 000 or 0000 as the case may be), it is polished, which is done by means of a piece of broadcloth to which polishing powder and water are applied. When all the fine scratches have been removed the section is washed in water and placed in a small dish of absolute alcohol or ether to remove the water and grease from the surface. The specimen is then dried in a blast of air and when possible placed in a desiccator to preserve the polished surface. The section thus obtained may be directly examined under the microscope when the constituents of the metal are of sufficiently different color to be distinguishable without further treatment. Direct examination will, for example, show graphite in cast iron or slag and manganese sulphide in steel. Once in a while it may lead to erroneous conclusions, as, for example, it was probably as a result of direct examination that the belief in the fibrous structure of wrought iron arose. Under a low magnification wrought iron with its strings of slag does give an impression of being fibrous, even though the metal itself, as we now know, is crystalline. In the majority of cases, however, it becomes necessary to develop the surface in order to gain a more complete insight into the structure of the metal. This development is done usually by chemical means, although other means are available. One of the most interesting of these is the so-called "heat tinting," based on the fact that steel heated in the air forms oxides, the colors of which depend on the thickness of the film formed and its character, both of which in their turn depend on the composition of the material. The result is that a series of interference or temper colors is produced. This method was used for the determination of phosphorus enrichment in steel, also to distinguish phosphide of iron from the carbide of iron in white cast iron, etc. However, the application of this process thus far has been only a limited one. The practice of chemical development or etching is based on the idea that the reagents used do not attack all the constituents of metals in the same manner. It is like making a mosaic out of bits of tile and bits of sugar and then applying a stream of water which will wash out the sugar

and reveal the distribution of the pieces of tile. In order to obtain a clear picture of the etched surface a considerable amount of knowledge is required in the selection of the reagents, and it is usual to specify what reagents have been used in etching a specimen inspected or photographed. Etching reagents may be applied either at room temperatures or slightly above them, or at quite elevated temperatures of the order of molten calcium chloride. This latter is used for the purpose of developing the structure stable at certain high temperatures.

Ordinary etching reveals the structure of a material but fails as a rule to give information as to strain lines, i.e., alterations in the body of steel caused by stresses.[15] A process has been lately developed employing as an etching medium a strong acid solution of copper chloride over a properly prepared steel, and it is claimed that this brings out a set of lines which from all information available appear to be strain lines.

Deep etching develops differences in color between different grains, some appearing dark and others light. It may be stated in this connection that notwithstanding the very great progress already made and the results achieved, microscopy as applied to the investigation of metals is still more or less in its infancy and, for example, is far behind in its technique as compared with the art as developed by the biologist. Thus, next to nothing has been done to obtain reagents that will produce distinctive colors in the various constituents of steel beyond what may be called degrees of grayness.

Still deeper etching produces within certain grains geometrical figures which are called "etching pits." These etching pits approximate a definite geometrical form, such as a triangle or rectangle, and within any particular grain have the same form and orientation. They furnish additional evidence of the crystallinity of metals.

The Bureau of Standards[15] has recently undertaken an investigation with the aim of finding a rational rule by which one could be guided in the etching procedure. The present investigation deals with the identification of such constituents as are found in chrome, tungsten, vanadium, and high-speed steels. The conclusion to which the investigation comes is that neither the heat-tinting method nor etching with acidic solution offers satisfactory means of distinguishing between the alloying constituents of the above-enumerated steels. Solutions containing alkali and electrolytic etching present, however, a satisfactory means when properly used. Tungsten carbide can be distinguished from chromium carbide mainly by its characteristic crystalline form and not by its response to etching methods.

The surface prepared in any of the manners described may be investigated by the naked eye or under the microscope. It is comparatively rare that the former can be used, and usually magni-

fication is necessary in order to obtain useful results. Essentially the metallurgical microscope works in the same manner as all other apparatus of the same kind, but the details of construction make it different from the microscope used in biological work.

In ordinary work such as routine investigations of metals, magnifications of 50 or 100 diameters are sufficient as they bring out the general distribution of such constituents as pearlite, cementite, and martensite, and show the mode of distribution and appearance of graphite particles. They also reveal sufficiently for ordinary purposes the presence or absence of impurities and the degree of uniformity of the metal over a given cross-section. Where more exact metallurgical knowledge is required, magnifications of 500, 1000 and even more diameters are resorted to. Figs. 9 and 11 on pages 17 and 18 show similar structures, in the first case under a magnification of 100 diameters, and in the second, of 1840 diameters.[1] The appearance of the metal in these two views is strikingly different, and it may be suggested that for those who are not expert metallurgists accustomed to work with structures under high magnifications, lower magnifications may prove to be a safer guide, simply because one is naturally more familiar with the way a sound metal looks under the common magnifications of, say, 100 diameters, and the structure under that magnification offers a better ground for comparison. On the other hand, for research purposes the higher magnifications are of unquestionable value. In fact, an editorial in *The Iron Age* of September 11, 1924, discussed the possibilities of magnifications of 5000 diameters, and expressed the belief that they would tell us, for example, of the real atomic spacing and the nature of martensite. Here again metallurgical microscopy, being only a fairly young science and for a long time having been hampered by lack of proper recognition, has not yet reached the same stage of development as, for example, microscopy as used in physical chemistry and biology. In these sciences magnifications far in excess of 5000 have been successfully employed, and the ultramicroscope even permits one to see particles of matter much smaller than the shortest wave of visible light. The ultramicroscope and the use of the highest possible magnifications have been the means of revealing such mysteries of nature as the structure and behavior of colloidal solutions of metals, and the life and mode of propagation of some of the minute microorganisms. There is every reason to believe that higher microscopy together with X-ray analysis will contribute powerfully to our knowledge of the structure of metals.

There is another field where microscopy might afford some useful knowledge, but the difficulties in its application, particularly to metals like steel, are so enormous that at least for the present but little hope can be entertained that it can be done. This is the field of investigation of metals in their molten state and during the critical period of solidification.

Macroscopic Examination of Iron and Steel

It is only comparatively recently that serious attention began to be paid to examination of macrostructure of iron and steel, although the process itself is, of course, older even than microscopic examination. Macroscopic examination lacks the extreme detail shown by microscopic examination, but it has the advantage of showing the aggregate effect of these details, and on a scale which shows their relationship to the form and size of the section of material being examined. Besides furnishing direct information as to certain matters such as presence of non-metallic inclusions, macroscopic examination may be used also to select the spots which should be subjected to the more detailed microscopic examination.

In a paper before the American Society for Steel Treating,[19] F. P. Gilligan and J. J. Curran discussed in particular the macroscopic examination after a hot-acid etch. In this case the specimen is immersed in a strong solution consisting of hydrochloric acid in water alone or with sulphuric acid. (Proportions given in the original article.) Metal that is sound, homogeneous, and relatively free from inclusions or dirt is only slowly and evenly attacked by the acid. Inclusions are, however, quickly dissolved out and the metal itself is attacked more powerfully, due to the increased surface thus exposed. As a result metal containing large amounts of dirt evenly distributed will be deeply pitted throughout. The flow of metal in forging and heading operations may be disclosed by means of the hot-acid etch, applied preferably to the longitudinal sections, the changes in direction of "fiber" being usually quite prominent. The etch may also be applied to show effects produced in the steel after treatment and in service, as, for instance, hardening characteristics, grinding characteristics, fatigue characteristics, etc. A certain amount of skill and care must be exercised in this test.

Ultra-Violet Metallography

In the field of the application of special methods of microscopy to metallography a truly important advance is described by Francis F. Lucas.[20] In this, advantage is taken of the increase in resolving power which accompanies a decrease in the wave length of light employed, and an instrument has been built by the Zeiss Scientific Staff to order of the Bell Telephone Laboratories in which, by means of quartz parts, a wave length of $275\mu\mu$ is used. This brings it within the ultra-violet region of the spectrum, and quartz had to be used because ordinary glass absorbs ultra-violet light almost completely. The application and use of ultra-violet metallography requires a very high degree of skill. On the other hand, by means of this monochromatic method a sharpness of detail is produced which seems to be unattainable within the conventional apochromatic system. Ultra-violet light has selective

properties which should help to identify structures. For example, it appears that certain constituents of hardened steel absorb ultra-violet light more readily than do other constituents. It is quite likely that this same characteristic will be found in connection with other metals. It is known that many colorless organic subjects show the effects of selective absorption of ultra-violet light, and although they show no signs of color by white light, they respond to ultra-violet light as though colored.

The ultra-violet microscope can be said to have lived up to expectations. Crisp, brilliant images can be obtained which surpass in quality those obtainable with the apochromatic system. The potential resolving ability of the monochromatic system can be realized in practice, and the practical application of the ultra-violet microscope should develop much new information. The ultra-violet microscope is the most complicated of any within the realm of technical or scientific microscopy. It requires a highly developed technique for its successful manipulation and the specimens must be prepared with great care. The ultra-violet equipment appears to have a potential resolving ability probably greater than twice that of the apochromatic system.

The difficulty in the present ultra-violet equipment is to obtain real critical illumination. Even very slight decentering produces flares and inequalities of illumination which are wholly ruinous to definition.

Illumination

In general, illuminants used in microscopic examination of metals can be divided for convenience into two groups: those which are used to produce the so-called "critical" illumination—in which the source of illumination is reproduced by the objective on the surface of the microsection—and those used in a projection system. Critical illumination is intended principally for visual observation, while the other systems are designed to give a stronger illumination, such as is needed for photomicrography. The illuminant may be a gas light or an incandescent bulb such as the concentrated-filament Mazda lamp, and for photomicrography the calcium light and arc light. It has been suggested[2] that polarized light be used for the examination of objects. The attempt has not been quite successful but the idea is interesting. In a polarizer, such as a crystal of iceland spar or tourmaline, a beam of light breaks up into two rays of equal intensity; one known as the ordinary ray is reflected through the sides of the crystal and absorbed, while the other, the extra-ordinary ray, passes on through and is said to be a ray of plain polarized light.

The next thing with which one has to deal in metallurgical microscopy is the manner of illuminating the metal surfaces which have been polished and etched. Obviously only reflected light can be used, which is the reason why this class of examination has been

referred to above as reflection microscopy or photography; but the incident light may be made to fall upon the surface in several ways, and respective methods of illumination are known as oblique, vertical or normal, and conical. Oblique illumination is produced when a suitably arranged beam of light falls upon the metal surface from some direction outside the lenses of the microscope. It is very simple and valuable, especially where it is desired to take account of the differences of level and surface configuration. On the other hand, the optical effects produced may be exaggerated or distorted. Minute surface defects are apt to be emphasized and slight differences of surface texture appear as vivid contrasts of brightness. For certain practical reasons oblique illumination can be conveniently used only with lower powers of magnification, and is employed but little in photomicrography.

In vertical or normal illumination the light is caused to fall upon the surface of the specimen in a direction at right angles to the surface; i.e., if the microscope is used in the vertical position, the light falls upon the specimen vertically from above. Only a small part of the light used is actually employed to form the image, but this amount is sufficient for practical purposes, and with certain appliances very clear views can be obtained. One of the disadvantages of normal examination is that steel constituents are seen only in outline, no shadows being cast, while it would be obviously desirable to view microscopic objects in a more natural way, i.e., to see them in relief. This may become important at higher magnifications. To meet this situation a new method known as "conical illumination" was developed (by Harry S. George). In this method an opaque disk is placed in the optical system of the microscope in such a manner that an image of the disk is formed near the back lens of the objective, producing a hollow cone of light in the objective with the apex of the cone on the object. Because of the fact that the rays of light in this case are more nearly parallel to the optic axis and therefore are reflected back through the objective from plain surfaces, they make them appear bright and impart a natural relief effect to the appearance. Moreover, this method is adaptable to high-power work.[3]

Photomacrographs and Photomicrographs

It is but a natural step from the investigation of surfaces of metals by the microscope to the recording of their appearance by photography. The production and preparation of photomicrographs in metallurgy does not differ from the process used in other arts and therefore need not be especially described here. Mention may be made, however, of the fact that two main kinds of photographs may be taken: the "photomacrograph," where the picture is of the same size as the original, and the "photomicrograph," which is taken through a microscope and gives a magnified view of the original. The purposes of the two are entirely different. In photomicrog-

raphy the surface of the metal is etched in such a manner as to produce irregularities on the surface which will be shown by the reflection of the light. In this way the grain structure and the distribution of the various constituents of the metal are brought out. In photomacrography only the general structural distribution is brought out, the purpose of photomacrographs (which includes sulphur prints) being not to ascertain the grain structure as such, but to determine whether the article or ingot is of uniform chemical composition and to estimate its general structural distribution. Photomacrographs are produced by polishing the sample, etching it, and then photographing the surface. There are two ways of doing the latter, one by means of ordinary photographic apparatus, and the other—known as the contact process—by using specially sensitized paper which is laid directly on the etched surface. In this latter the etching materials and the material with which the photographic film (which may be of silk) is impregnated are of such a character that sulphide and phosphide inclusions are affected in such a manner that the parts of the film in contact with them change color and become lemon-yellow for phosphorus and black for sulphide spots. (Such photographs are also known as "sulphur prints.")

X-Ray Photography

X-ray photography has two entirely independent purposes: one to investigate metal articles with the aim of discovering possible defects, such as blowholes, contraction cavities, slag inclusions, etc.; the other, to investigate the crystalline structure of metals. The former has been applied successfully, for example, at the Watertown Arsenal, Watertown, Mass.,[4] where about 200,000 volts are impressed on the Coolidge tube, with an exposure of about one minute for 1 in. thickness of steel, about five minutes for 2 in. thickness, and about thirty minutes for 3 in. It requires a certain amount of practice to read X-ray films correctly, but once this is attained these films show the location, the approximate size and shape, and, with considerable certainty, the cause of defects in steel castings. Occluded sand, cavities resulting from incomplete deoxidation of the metal in the furnace, cavities formed by gases entering the metal during solidification from the core and mold, piping or shrinkage cavities resulting from inadequate feeding from risers during solidification, cracks caused by unyielding cores or failure to promptly relieve the mold, imperfections in welding and burnt-in metal, can all be individually detected.

Among other things, it has been found that where a number of castings have to be made from a given pattern, X-ray analysis can be employed to a certain extent as a means of improving the design of the pattern, thus insuring better castings. The principle on which X-ray photographs are used to discover a defect is that the rays which pass through a defect such as a blowhole, and there-

fore through a smaller thickness of metal than exists in the sound parts, reach the film with greater intensity and form a much darker spot on the film, the outlines and size of the spot corresponding closely to those of the defect.

X-Ray Analysis of Crystalline Structure of Materials

The ordinary microscope can show only objects not larger than the shortest wave of visible light. The limit of this is violet light, and under certain conditions the so-called ultra-violet light may be used for the same purpose. In ordinary microscopy a method has been found to observe bodies smaller than the smallest wave length of visible light. The principle of this method is to have the body itself act as a source of light usually reflected. This led to the development of the ultra-microscope which has rendered such valuable service in the field of investigation of colloidal suspension and is now being applied for biological work, such as the study of cancer. This method is, however, not conveniently applicable to the study of solid bodies. When we come to an attempt to investigate the structure of such solid materials as metals in the range beyond the ordinary microscope, we find that today there is no known method of doing it by means of visible light. Fortunately another method is available.

To investigate, for example, the atomic structure of metals, it is necessary to have some kind of a ray that will be visible either to the eye or to a photographic plate and that will have the right length for this purpose, and it so happens that X-rays emitted by apparatus such as we can conveniently construct and use are either waves of just the right length, which means that they are of the same order as or rather a little shorter than the dimensions of the fine structure to be examined.[21] Here advantage is taken of a certain strong tendency in nature for regularity of arrangement.

It is a striking fact revealed by X-ray analysis that not only metals but many of the substances which have been hitherto regarded as being non-crystalline really possess a crystalline structure and have their properties dependent upon that structure. Amorphous carbon, for example, has been found actually to consist of minute crystals of graphite, which makes its present designation an obvious misnomer. Even colloids, substances usually regarded as typically non-crystalline, have been shown in some cases to consist of minute yet perfect crystals. Thus, for example, the most recent investigations indicate that rubber is of a crystalline structure, and there is every reason to believe that its very high elasticity is due to this fact. Some types of synthetic rubber hitherto produced have had the exact chemical structure of natural rubber but lacked the crystalline structure of the latter, and therefore also its elasticity. The atoms of which

a metal is composed are always found to be more or less in ordered array. One and the same pattern of arrangement may not, indeed, extend through the whole specimen. There may be breaks on each side of which are arrangements that are similar but do not dovetail into each other. Regularity is always there, however, and a portion throughout which the regularity is continuous in a single crystal; usually a mass of metal is an aggregate of minute crystals oriented in different directions, though under certain conditions an orientation substantially in the same direction can be produced. Those metals which have been hardened by cold work are softened by heating to a suitable temperature, and this softening is accompanied not only by the restoration of ductility, but by a substitution of a clearly crystalline structure of equiaxed grains (i.e., grains whose diameters are approximately the same in all directions) for the disordered structure found after cold working.

Finally, and this is what makes the new analysis possible, whenever there are waves and regularity of spacing which is of the same order of magnitude as the length of the waves, there can result a certain measurable phenomenon called diffraction. The spacings of the striations of mother of pearl are of the same order as the lengths of light waves, hence the diffraction colors that play upon its surface. The diffraction effects observed on the grating spectrometer allow us to compare the wave lengths of light with the distance between two lines of the grating. In the same way there will certainly be some kind of diffraction effect when X-rays traverse a body in which there is regularity of arrangement. The usual wave length of an X-ray is somewhere about the hundred-millionth of a centimeter, an Ångstrom Unit, so called. The dimensions of the pattern on which the atoms and molecules of the solid are arranged are generally a few such units in magnitude; for example, the distance between the centers of two neighboring atoms in a piece of aluminum is 2.86 Å. U., in α-iron 2.47 Å. U., and in γ-iron 2.57 Å. U. In these three cases the unit of pattern is very simple and consists of one atom only. In the majority of substances the unit is more complicated, and may contain ten, fifty, a hundred atoms. The regularity consists in the even spacing between a point representing one unit and a point similarly representative of the next.

Since there is regularity of spacing in a solid, and since the X-rays are of proper length in comparison with that regularity, there ought to be diffraction effects of some kind; and if we can find them we ought to be able to compare the periodicity of the spacing in the solid with the wave lengths in the X-rays. If we can go on to find how that regularity depends on direction in the solid we should be able to lay out the details in the pattern. To take a very simple example, if we were told that the distance between the rows of vines in a vineyard was 10 ft. in a north-and-south direction and the same east and west, but rather more than

fourteen northeast and southwest, it would be easy to find the pattern of the planting.

If a pencil of X-rays having one definite wave length be caused to sweep through or over a crystal, say, of aluminum, it will be possible to turn the crystal into various positions until suddenly a reflected ray flashes out. When that occurs the pencil of X-rays makes a certain angle with the reflected ray, an angle depending as regards size upon the magnitude of a certain spacing in the crystal.

The "Powder" Photograph. Suppose the crystal were turned round about the X-ray pencil. The conditions for combination would not be affected, and if the X-rays were acting all the time, the spot cast by the reflected beam would be extended so as to form a circle on the plate, with the strong spot cast by the primary beam as its center. To obtain this result, we must first set the crystal into a reflecting position and then rotate it about an axis coinciding accurately with the direction of the incident rays.

Now, suppose that not a single crystal but a small powdered mass of the substance is used. The vast majority of the crystalline fragments will not be in a position to reflect at all; but there will be some which are correctly adjusted, and these will produce spots on the plate. Since among the reflecting crystals there will be some that take up all the possible orientations of the single crystal revolving round the axis of the X-ray pencil, the result will be the formation of a ring on the photographic plate. This effect is easily obtained. In fact, when a fine pencil of X-rays of definite wave length is sent through a specimen of powdered aluminum, not only one ring but several rings are found upon the plate.

The characteristic of the system of rings changes with the structure of the material. Photographs of α-, β-, and δ-iron are quite different from that of γ-iron, the atoms being arranged in a different way. There are two ways of packing spheres, such as cannon balls, closely together—one in which there is a repeat every third layer and one every second layer. Aluminum and γ-iron follow the former. The unit of pattern is very simple in this case, merely a single atom. The other phases of iron follow the latter arrangement.

Now, if the metal experiences any mechanical treatment, the particles are put into partial order. Therefore any such treatment will alter the appearance of the photograph because the rings can no longer be complete. The rings will remain, but they shrink into spots on the circumferences. Faint radial lines appear due to inhomogeneities in the X-rays, which were not apparent in the simple picture because they were diffused all round the compass. The skilled observer learns to interpret the effects observed, and much useful information has already been gained.

A powder gives complete rings. There is another way of obtaining a photograph, and that is by taking a single crystal. If such

a crystal is subjected to monochromatic X-rays there will be no reflected ray unless it is correctly held. It must be disposed so that some plane of points in the crystal makes the proper angle with the X-rays, and only then the reflection flashes out.

There are several such positions, in each of which one of the many planes can be drawn to include the representative points in which the crystal is prominently involved. But it is not likely that any chance holding of the crystal will give a reflection. Suppose, however, that the crystal is made to revolve about an axis perpendicular to the X-rays. The inclination of the rays to the various planes will change continuously over wide ranges during the revolution, and reflection after reflection will flash out as each set of planes, and therefore each reflected ray makes its own characteristic angle with the incident beam. The resulting photograph will show a collection of spots, and it may be expected that the ordered array in the crystal will give order to the photographs.

Suppose now that instead of taking a single crystal and rotating it, a number of minute crystals are taken, arranged so that some one common direction in them all is parallel to a certain straight line and perpendicular to the X-ray beam, but otherwise their disposition is a matter of chance. The substance may be said to possess a "fiber" structure. We should then expect the same picture as when we rotated a single crystal. In the first case, one crystal occupied all possible positions successively; in the second case, different crystals occupy all possible positions at the same time. A good example is given by a set of asbestos fibers, each of which is crystalline. One definite direction in each crystal is parallel to the length of the fiber, and the bundle of fibers is placed perpendicularly to the X-rays.

Examination of the inner structure of metals by X-rays has not only a great scientific interest in that it reveals the structure of the metals, but a practical value as well. It has been applied, for example, to the examination of the inner structure of strained metals such as drawn copper wire. Experiments show that a copper rod composed of an irregular mass of small crystals as a result of rolling or forging and being drawn into wire takes a fibrous structure, the arrangement of crystal lattices being transformed into a state of irregularity which may account for the changes in such properties as hardness and strength.[5]

Lately the monochromatic pinhole method has been applied for the practical identification of working and heat-treating processes of metals and for similar purposes.[22] In the monochromatic pinhole method a molybdenum water-cooled-target Coolidge tube operated at 20 milliamperes and 35,000 volts is enclosed in a lead box through the walls of which are inserted heavy brass tubes about 8 cm. long and 3 cm. in diameter, provided with lead plugs fast in each end, through which pinholes are made accurately in line by

centering in a lathe. The specimen is fixed over the outer pinhole so that the beam grazes it at a definite angle. Apparatus is now available consisting of a steel-lead cylinder in which the tube is placed coaxially so that 18 pinhole and powder diffraction photographs around the cylinder may be taken simultaneously. The value of the monochromatic pinhole method lies in the fact that it discloses that a whole series of specimens with the same fundamental iron lattice may show vastly different properties because they have been worked or heat treated differently.

By means of this method applied to a hot-rolled piece of low-carbon steel the rolling direction is made clearly evident, as the rolling has produced an orientation of the grains. An inspection of a similar photograph of a cold-rolled piece shows the radial lines much sharper, indicating the much greater fragmentation and exact orienting force applied. A photograph of ordinary tinplate shows how the tin crystals apparently tend to deposit from the melt in the oriented fashion.

Determination of Corrosion Resistance

There is really no such thing as a universal factor of corrosion resistance.[8] Materials which are highly resistant to one agent, such as sulphuric acid, may prove to be entirely incapable of resisting another one, such as nitric acid. Corrosion-resistance tests should always be made clearly with a view to the factors which may affect the material while it is in service; thus it would be entirely useless to test the iron members of an inland building for corrosion resistance to salt water. Because of the great diversity of corroding factors, numerous tests have been developed for corrosion resistance. The investigation made by the Bureau of Mines as to the corrosion resistance of various materials when exposed to mine waters[9] is a good example of the method used in carrying out such tests.

Quite often it is desired to know how a certain material will behave when exposed to corroding factors over a great length of time. Such is the case, for example, with soil pipe, which, under certain conditions, may not start corroding until it has been in the ground for a period of, say, 10 to 20 years. In such cases it is desired to have some quick test that will within a reasonable period, of, say, a couple of months, give a more or less reliable indication as to what behavior may be expected from the material over a long time. Such tests are called "accelerated corrosion" tests, and it should be clearly understood that by no means all of them are fully reliable. Whenever such a test is used it is well to accept its conclusions with a certain amount of circumspection and to investigate whether it has been used on a similar material long enough to afford a basis of comparison between laboratory results and the behavior of the material tested under actual service conditions.

The subject of corrosion resistance is frequently rendered more complicated by the application of protective media to the metal parts.[10] The presumption in such cases is that the protective medium, such as paint, tar, etc. will help delay or prevent corrosion. Whether it does so or not is a matter that it is well to determine and not take for granted, because in matters dealing with corrosion things do not always work out quite as simply as one would offhand expect them to. For example, one might suppose that two layers of paint would protect metal from corrosion better than one layer, and yet cases have been found where two layers reduced the amount of corrosion protection to less than that afforded by one layer.

Another element in connection with corrosion tests which has to be borne in mind carefully is that of seeing that the tests involve all the factors present in actual service. For example, if there is a possibility that stray currents from electric traction lines may be flowing where the pipe or other part under consideration is to be laid, tests of corrosion by electrolysis should be carried out. In districts like Pittsburgh, sulphurous, hydrofluoric, and silico-hydrofluoric acids may be present in soil waters through being introduced therein by rain and condensation from the air into which they are projected by the numerous steel mills, glass works, and chemical plants. Therefore tests for the corrosion of parts to be imbedded in Pittsburgh soil which were carried out with Croton water in New York City might not give valuable results. It should be also clearly understood that in a complete machine a member may corrode with great rapidity because of contact with, or even nearness to, other metal parts made of materials having a different electric potential. Hence, in testing for corrosion attention should be paid to the influence of other parts of the structure. One famous case is that of a yacht having a steel hull and monel-metal sheathing where violent corrosion of the steel parts took place, obviously due to high electric potentials set up by the contact between steel and monel metal in sea water. Here corrosion tests of either steel or monel metal alone would not have given any information that would have been useful to the designer of the yacht.

In many cases only the surface of a metal is protected against corrosion, and in these it is important to consider whether in the use of the article this surface is likely to wear off, and in that event what happens to the metal. It is also important to note whether parts of the surface may be cut away, as, for example, in cutting threads on a pipe, and what will happen then as a result of the interaction of the protected top layer and unprotected lower layers. Galvanizing, sherardizing, and galvannealing (zinc coating) and nickel plating are the best-known methods of protecting the surface of the metal. Lead plating, cobalt plating, and chrome plating are receiving increasing attention. A different type of surface pro-

tection is presented by calorizing and chromizing, both of which consist in heating an iron or steel article in aluminum or chromium powder in an atmosphere of hydrogen under conditions which produce a sort of alloying action between the two metals, resulting in a heat-resisting, and to a certain extent corrosion-resisting, surface layer. It is important to remember also that the so-called "stainless steel" (steel containing a very low percentage of carbon and from 10 to 14 per cent chromium) is stainless only if the surface is polished.

Reference was made to a method of protecting the surface against certain forms of corrosion and heat action by chromizing. As practiced today the chromizing process consists of heating an article in a mixture of aluminum and chromium powder in an atmosphere of hydrogen. This involves certain difficulties which materially raise the cost of operation, one of the most important factors in this direction being the necessity of using a complicated three- or four-stage process of purifying the hydrogen so as to free it from all traces of oxygen and water vapor. However, Jos. Laissus[23] describes a new method of chromizing. In this the steel to be chromized is placed in an iron tube filled with powdered ferrochromium. This tube is carefully closed and luted with a mixture of fireclay and carborundum powder and placed in a second iron tube filled with cast-iron shavings and luted in the same way as the inside tube. In this way the use of hydrogen with all its concommitant difficulties is eliminated and a comparatively simple process employed. It is desirable that the operation be performed in a reducing atmosphere. Tests made by the author of the process have shown that a considerable amount of chromium is obtained, and that it is possible to give a finished article a beautiful surface polish. The same method also made it possible to obtain a chromizing effect by using an electrolytic chromium powder of high purity. The paper by Laissus referred to here gives full data as to the temperatures and durations of operation employed.

Often a photomicrograph of a material may give an idea, very approximate only of course, as to the behavior of a material when exposed to corroding agencies. In general, the more uniform the structure of a material is, the less it is likely to be subject to corrosion.

Determination of Electrical Properties

This is a subject with which mechanical engineers have seldom to deal, electrical properties of metals such as electric conductivity, magnetic properties, electrolytic potential, permeability, etc. being of greater interest to electrical engineers, who have developed very precise methods of testing for their determination.

Determination of Physical Constants

There are quite a number of such constants, some of which are

of interest to mechanical engineers while others are not. The melting point has been fairly closely determined for the great majority of metals and their alloys, and the values can be found in handbooks. The latent heat of fusion has been determined for a number of metals and this information is scattered through a number of publications. It is not usually of interest to mechanical engineers. The coefficient of thermal expansion has been determined for a number of metals and alloys and varies from zero at ordinary temperatures for invar (an alloy of iron and nickel) to very appreciable values for such alloys as nichrome and metals like zinc. This is obtained directly by raising the temperature of a bar of a given length through a desired range and measuring it before and after heating, and is quite well known for the great majority of metals and alloys. It is important in this connection to remember that metals have two coefficients of expansion, i.e., the linear and the cubic, and in engineering work it is often well to distinguish between the two. There is a third factor belonging in a way to the same class, viz., contraction on freezing. The majority of metals (cast iron is one of the few exceptions of commercial importance) shrink on passing from the liquid to the solid state, a fact which has to be taken into consideration in the design of patterns for castings. In steel this shrinkage is assumed to be of the order of 2 per cent (say, $^1/_4$ in. to the foot).

Determination of Stability

This test is not necessary for all metals, but it so happens that certain metals change their structure with time and become brittle. This phenomenon is called "aging" and is said to affect duralumin, for example.

Because of this, when a new alloy is developed it is a wise plan to have samples retested at certain intervals to determine whether or not aging has to be considered. No reliable accelerated test for aging appears to have been developed as yet. There is another condition somewhat similar to aging which should not, however, be confused with it, namely, the deterioration of a material exposed to high mechanical or thermal stresses over a considerable period of time. Thus elevator cables lose their strength after a certain period of service; annealing containers become brittle, etc. Here we have to deal not with aging but with fatigue in one case and change of crystal structure in another. Because of this, where it is expected that a metal member will be in service under stresses, mechanical or thermal, approximating the danger line, it is well to institute tests for its structural stability under such conditions after various lengths of service. The somewhat indefinite expression "danger line" is used advisedly, because of the great variation in what it may imply.

A phenomenon somewhat similar to aging is likely to develop in metals subjected in service to high temperatures for great lengths

of time. Such metals, unless of compositions specially adapted to this kind of service, will probably deteriorate and lose their strength. There is no standard quick test for this condition.

As to the methods of testing for stability, all that can be said is that they will vary with conditions of service; but in all cases it is advisable to have a microscopic examination of the metal carried out side by side with the physical tests, as in the vast majority of cases changes in physical strength are accompanied by recognizable changes in the structure of the metal.

Magnetic Analysis

The majority of tests to which metals are subjected, such as tensile tests, chemical analysis, etc., are of a destructive character, which means that the piece tested is destroyed during the test. Because of this the test can be carried out only on a sample, and the conclusion reached is limited strictly by the extent to which the sample tested represents the actual properties of the material. In certain branches of engineering where tests on models (and a test bar is after all nothing but a crude model of the actual article) are extensively used, an attempt has been made to develop what are known as "laws of similarity," or laws defining the relation between the properties of a small-scale model and a large-scale article. In aeronautics, in particular, where scale models are tested in wind tunnels, the law of dynamic similarity has been developed to a considerable extent.

Obviously, destructive testing can be used only on samples or on actual articles after they have outlived their usefulness, or finally in investigating causes of accidents which have already occurred. There would be but little profit in determining that an elevator cable is sound by tearing it in two, and it is desirable to have a method of non-destructive testing of materials even when their indications are only approximate. The magnetic testing of steel is such a method, as also is X-ray investigation.[17]

Comparatively little has been published on the magnetic testing of steel. It is stated it was developed in a more or less accidental way. For some reason it was desired at the U. S. Bureau of Standards to make up several steel bars having the same magnetic permeability. This seemed to be a very simple matter, but when an endeavor was made to get such bars it was found that scarcely any two bars have the same permeability. A further investigation showed that the permeability of a piece of steel varies in a decided way with the slightest variations in its composition, and, for example, that the presence of pipe, slag inclusions, segregations or flaws causes a clearly noticeable change in the magnetic properties of the metal. This clearly indicated the possibility of using magnetic testing for the discovery of imperfections and variations in steel.

As an example of the actual method of testing may be cited

the use of the "defectoscope," which is an apparatus invented by Dr. Charles W. Burrows and described in *The Iron Age* of October 28, 1920, pp. 1125–1128. This device comprises a magnetizing solenoid and a detector, the latter consisting of two test coils having the same number of turns and surrounding the specimen.

The magnetizing solenoid and the detector are rigidly connected together and are given a relative motion along the length of the specimen by means of a suitable motor which forms the third element of the system. As the detector occupies different positions along the length of the test material, it is threaded by an induction which depends upon the nature of the specimen. If the specimen is not quite uniform the magnetic induction threading one of the coils of the detector is different from the magnetic induction threading the other coil. The result is the electromotive force generated in one of the test coils is different from that generated in the second test coil. Consequently a small differential electromotive force is impressed upon the detector system every time it passes over the magnetic inhomogeneity.

Determination of Machinability

There are no standard tests for machinability, cold and hot working, and forging. In ordinary steels the behavior in respect to these factors can be predicted roughly from the composition of the steel and its heat treatment, and often depends far more on the latter than on the former. In new alloys it has to be determined by test.

As regards machinability, however, it should be noted that in a large number of cases this depends also on the uniformity of the structure of the steel. In a soft steel hard spots may be encountered which make the machining very difficult. Chromium steels are particularly subject to this condition and so are certain kinds of cast iron. This condition may be determined at times by taking photomicrographs at various spots, but sometimes only by actual tests. Attempts have been made to determine the machinability of a material by measuring its surface hardness. Such a test may give valuable results provided that a sufficient number of spots on the surface of a metal are tested, and provided further that the test is sufficiently delicate to determine not only the average hardness but also the actual hardness of the entire surface. Where none of the short-cut methods are applicable, only an actual trial can be used. Where a test for machinability is made the following information should be available as supplementary to the actual cutting results: Method of casting, forging, or rolling the samples; whether or not the casting skin has been removed, as by grinding or pickling; what heat treatment, if any, the test piece has been subjected to (this information is not necessary when dealing with a rolled product, but may be of value in dealing with forged products); what cooling liquids, if any, were used in the cutting test; cutting-tool

material. If cutting tests indicate the presence of hard spots an investigation should be made to determine their nature and origin as well as the possibility of removing them by proper heat treatment.

Tests for cold and hot working are usually made only when dealing with new alloys as the behavior of the standard steels under these conditions is well known.

Tests for Workability

A test has been developed to determine how the given metal may be expected to behave in the draw press. This is done by means of the Erichsen ductility testing apparatus.[14] This consists essentially of a die and holder for holding the sample to be tested and an internal tool actuated by a handwheel which moves gradually forward until the sample is ruptured. The progress of the internal tool and the ultimate fracture are observed in a mirror and the depth of indentation is read directly from a micrometer-graduated screw. One of the features of this test is the evidence it gives of approximate grain size of the metal tested. This makes this test valuable as a guide to drawing operations on annealed metal, since another annealed metal will rupture in deep drawing owing to its hardness and lack of ductility, while over-annealed metal will rupture because of the weakened condition of the metal, resulting from excessively large grains.

Determination of Erosion Resistance

Erosion is a form of wearing away encountered in guns and the blades of steam and gas turbines. While there is no standard test for its determination, an article in the *Brown-Boveri Review* for December, 1924, describes a test by which erosion resistance may be determined in something like 70 hours. The method consists in placing a carefully weighed specimen in such a way that dry saturated steam impinges on it at a certain angle. After the test the specimen is carefully dried and reweighed, the decrease in weight serving as a measure of the liability to erosion of the material concerned. The appearance of the specimen also indicates—often very clearly—the erosion strength of a material.

From this test it has been found that increase in hardness due to proper heat treatment produces a notable decrease in the loss due to erosion.

Spectroscopic Analysis

Spectroscopic analysis has been primarily used principally for the determination of constituents of materials occurring in such minute quantities that it is difficult to identify them by ordinary chemical analysis. The equipment used in scientific laboratories is entirely unsuitable for ordinary metallurgical work, and it is extremely seldom that elements occurring in such minute quantities as to warrant the application of spectroscopy affect the structure of metals

or their properties to an extent that would interest an engineer. Lately, however, apparatus has been placed on the market in England that enables the presence of nickel and chromium in steel to be detected immediately, even by an unskilled observer. It is stated that with a few days' experience with bars of known nickel and chromium content, the observer learns to judge the approximate percentage present.

The spectroscope employed consists of a substantial casting with two screw-focusing eyepieces at one end and a stout protective glass plate at the other. The method of use is extremely simple. In the case of the instrument designed for testing bars in the rolling mill or warehouse, one bar of carbon steel is held in a suitable wooden frame, and the bars to be tested are then placed in position on V-supports one by one as rapidly as possible, connection with the electric mains being provided through a suitable resistance giving about 5 amperes. Direct current of from 150 to 250 volts is necessary. The arc is struck by touching both rods simultaneously with a third rod of iron or carbon steel (insulated by pushing over one end of it a piece of ordinary rubber tube). Removal of this rod strikes the arc, and the observer at the spectroscope is able to state immediately whether or not the sample contains an important quantity of nickel or chromium. With the aid of three or four standard samples containing various percentages of nickel and chromium he can soon accustom himself to state also the range of percentage within which the nickel or chromium content lies.[5]

Testing by Sound

This is one of the oldest tests, the expression "steel that rings true" having been used from the oldest days by blacksmiths and swordmakers. For various reasons it has not yet developed into a practical method of testing, but its possibilities were indicated by Prof. Henry M. Howe in his presidential address before the International Association for Testing Materials at the meeting in New York in 1912, when he stated: "Who shall say that the pitch or volume or timbre of sound emitted by a rail as a result of a given excitement may not be made to disclose pitilessly its hidden defects and to measure the fitness not alone of the material of which it is composed but of the rail as a whole structure? Or, giving rein to our fancy, we hear the inspector report, 'This 100-story building indeed responds to G sharp, but its timbre has this abnormality and these harmonics are exaggerated.' "

Sound testing in a somewhat modified form has recently been employed to detect flaws developing during the process of forging as a result of stresses set up during the heating and the cooling processes through which the forging passes in the course of its manufacture. The instrument used does not detect flaws in a cold forging. Its operation is based on the fact that flaws of this character, which are also called "clinks," are accompanied by a ringing noise

at the time of their formation, and detection of this sound by a continually operating recording apparatus forms the basis of the "Clink Detector," as the instrument has been called by the makers. The detector is attached to the forging under observation during the heating and cooling process, and on a clock-driven recorder which is electrically connected to the detector a record is obtained of any shock or disturbance occurring in the body of the forging. The instrument can also be adapted for recording the temperature of the forging during the various processes of manufacture.[7]

A Method of Observing Flaws in Metal Surfaces

This is very important and yet not easy to detect, because in rolling some of the metal may be "smeared over" the surface in a very fine layer and thus hide to a large extent the presence of cracks. An apparatus has been described[24] in the past two years which has been primarily developed for observing by a direct-deflection method small changes in the effective resistance and inductance of a coil, but which also may be effectively used for detecting flaws and cracks in the surfaces of metal articles. The principle of action of the apparatus is based on the following. When a coil of wire through which an alternating current is flowing is brought near a piece of metal, currents are induced in the metal which have the effect of producing an apparent increase in the impedance of the primary coil, the change in the impedance being a function of the resistance offered by the metal to the induced secondary currents. The resistance offered to the induced secondary currents depends on the conductivity and thickness of the metal plate, and if the change in effective resistance or inductance of the coil is measured, this change will enable the conductivity of the metal plate to be estimated for a given size and shape of coil.

The apparatus, however, may be used to detect flaws and cracks in a metal plate since the slightest crack in the metal is sufficient to put a very high resistance in the path of the induced secondary current in the material of which the plate is made, causing thereby a change in the balance of the Wheatstone bridge. The apparatus consists of a bridge network, with two inductive arms, which is normally balanced. The bridge is supplied with alternating currents, the indicating instrument being a d.c. galvanometer connected through a synchronously driven commutator. One of the arms of the bridge contains the "exploring" coil, which is placed on the metal surface to be examined, and if the commutator is so adjusted as to indicate the current in phase with the applied voltage its deflection is proportional to the change in effective resistance of the exploring coil. With the commutator adjusted to observe currents 90 deg. out of phase with the applied voltage, the deflection depends on the change in effective inductance of the coil when this change is brought about by the presence of a metal plate. For non-magnetic materials it is best to use the com-

mutator in the "out of phase" position. The change in effective inductance depends on the specific conductivity of the plate, and the apparatus may be used for quickly comparing the specific conductivities of metal plates. If such plates have cracks normal to the surface, their presence is indicated by a reduction in the galvanometer deflection as the coil passes over a crack.

Dilatometric Analysis

This method is based on a well-known fact that the volume of a steel or piece changes on heating or cooling the latter through its critical point (compare matter on dilatation on page 88). There are several devices now on the market in this country and Europe making use of this phenomenon. One such device is described by O. E. Harder, R. L. Lowdell, and A. C. Forsyth.[25] In the discussion of this paper R. W. Woodward showed a Rockwell dilatometric outfit attached to an electric pit-type furnace. The equipment as shown is arranged with an indicating dial to show the expansion of the steel progressing throughout the critical transformation range and also an autographic attachment which produces a continuous record of the length changes.

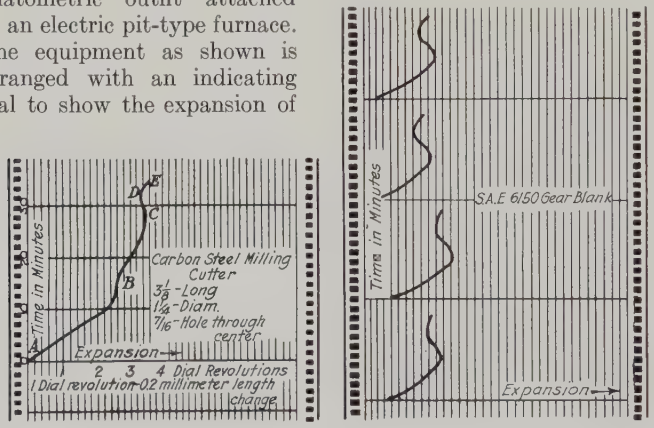

Fig. 22(*a*) Characteristic Dilatation Curve on Carbon Steel

Fig. 22(*a*) shows a record as produced in the hardening of a carbon-steel milling cutter. Point *A* on the chart indicates the dimensional size at the time the work was placed in the previously heated furnace, but with the heat supply shut off and the dilatometer brought in contact. The work expands at a decreasing rate to the point *P* corresponding to the amount of residual heat in the furnace. In other words, at the point *B* a temperature equilibrium between work and furnace exists, and all parts of the work are equally expanded. At *B* the fuel supply to the furnace is again applied so as to bring up the temperature of the work and the furnace at the same rate. Expansion of the work is again resumed

and decreases slightly before the point C, at which point there is a reversal in the direction of the curve. This reversal marks a contraction in the work, and is an exact indication that the steel is entering the critical transformation range. This contraction continues until the transformation is completed at D on the curve. At the completion point D reexpansion then takes place, at which time the work is removed from the furnace for quenching. As a convenience to the operator an alarm attachment is provided so that a bell rings when point C is reached, and continues to ring until point D is reached. It is also possible through suitable relays to arrange so that an additional signal is given when the point D is reached and the hardener is forcibly reminded that it is time to quench the article.

A method based essentially on the same principle, but using a different apparatus has been developed in Europe. There the apparatus used for the determination of the dilation (called "differential dilatometer[26]) utilizes a suitable standard sample which is heated to the sample temperature. The expansion of the same under test is then compared with the expansion of the standard sample and the difference between the two is determined. The apparatus is so designed that a beam projected by a mirror photographically makes a curve of which the coordinates are the expansion of the standard sample and the difference in expansion of the two samples. Considerable care has to be taken to keep both samples constantly at the same temperature. The apparatus if properly used permits determining the character of graphitization in a cast iron.

Dilatometric analysis possesses, as does chemical analysis, a dual aspect: (*a*) Qualitative Analysis. The specific directional changes at definite temperatures, as that of cementite, characterize the presence of phases, definite aggregates or solid solutions of which the chemical composition is known. But, though chemical analysis indicates the mass composition of an aggregate, dilatometric analysis gives information as to the nature of the aggregate, and thus constitutes a process of immediate analysis. (*b*) Quantitative Analysis. The size of the directional changes.

Dilatometric analysis is applied not only to large samples obtained by casting or machining, but also to rods prepared by the agglomeration of powdered material. Thus it is now possible to study industrial reactions which exist in the solid state such as roasting, cementation, etc.

Finally, independent of dilatometric analysis, the differential dilatometer allows of the measuring of expansions in an extended temperature interval, such as the working of a part in machines operating at high temperatures, the choice of foundry enamels, optical glass apparatus, glass soldered electrodes, etc.[27]

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CHAPTER IV

HEAT TREATMENT

The knowledge of the fundamental principle of heat treating goes back into the mists of prehistory.[1] Homer, some ten centuries before the beginning of our era, describing the blinding of Polyphemus, said, "And as when a smith dips a great ax or adze in cold water amidst loud hissing to temper it—for therefrom comes the strength of the iron—even so did his eye hiss around the stake of olive wood."

The big things metallurgists have since learned have been, first, how to heat treat material more effectively, secondly, that not always "therefrom comes the strength of the iron," but instead, that improper heat treatment may weaken the material rather than strengthen it.

From what has been said in the first two chapters of this series, it would appear that the properties of a material depend primarily upon two factors, its chemical composition and its structure, the latter being taken in the broad sense to cover both the crystalline and the intracrystalline distributions of material. Either the chemical composition of steel or its structure can be changed within wide limits, even after the steel has reached the solid state.

Experience has shown that steel of any given analysis attains its desirable properties at a certain composition and structure, and further, that steel as cast very seldom possesses these desirable chemical compositions and structures. The problem of the metallurgist is therefore to take the material as produced by casting, rolling, or forging and by means of heat treatment impart to it that chemical composition and that particular structure which will give it the desirable qualities. Roughly, it has been found that many desirable qualities may be imparted to a steel of given analysis—and to a certain extent to cast iron—by heating it to a given temperature and then cooling it in certain ways to another predetermined temperature and "trapping" the composition and structure of the metal which has been thus created; or else by heating it to a certain temperature, cooling it to another temperature, and then reheating it to a temperature below that to which the metal was first heated. Various combinations of these methods may be also used.

The need for heat treatment may originate in several ways. When a casting is poured in its mold its rate of cooling obviously depends on the thickness of section, a heavier section cooling at a lower rate than a thinner one. Furthermore the loss of heat from the casting is practically beyond the control of the foundryman. As a result of these two conditions, it is only very rarely that a casting has the same grain structure throughout, and it is equally rare that the temperature conditions and rate of cooling during the

solidification and subsequent chilling of the casting are such as to produce exactly the right structure therein. It usually happens that the wrong structure is produced instead, and heat treatment has to be called upon to correct this state of affairs.

In the case of alloy steels particularly, it is often absolutely essential in order to impart the necessary properties to heat the material to a certain temperature and to cool it in a certain manner or at a rate entirely different from that prevailing in a casting when chilled in the mold. A good example of this is the well-known case of high-speed tool steel.

Another important instance where heat treatment is essential is in the case of materials which have to be first soft and then hard. Such is the case of ball-bearing races. This material must be soft initially in order to permit the cutting, trepanning, and machining in the automatic, but afterward must be extremely hard in order to withstand the mechanical stresses imposed upon it and the cutting action of the hard balls.

A third group of cases where heat treatment is essential has to do with metal wherein hardness has been induced by cold working.* Thus in cold-drawing tubes a single pass through the dies hardens metal which was quite soft before the operation to such an extent that if it were attempted to put it through the next pass on the bench without previous treatment it would not flow but would crack. In all such cases it becomes necessary to submit the metal to some operation that will make it softer.

It has also been found that heat treatment, in addition to changing the hardness of a metal, may increase or decrease its tensile strength, resistance to vibration, and other properties. In fact, there are many instances where heat treatment produces some of these effects without materially changing the hardness of the metal. Such for example, is the case with the so-called Hadfield manganese steel.

From what has been said in Chapter III, dealing with the structure of steel, it appears fairly clear why heat treatment produces these various effects. To recapitulate in a somewhat different form the information given in that chapter, it may be stated that these effects are produced by two factors: At certain high temperatures all ferrous materials are essentially solid solutions of carbide of iron and carbides (and possibly other combinations) of the alloying elements in certain allotropic modifications of iron. No matter what the structure of the material may have become at room temperature, as an effect of mechanical working or previous thermal influences, this structure may be, at least for a given material, and often is, completely destroyed by passing the material into the state of solid solution, just as the shape of lumps of sugar may be destroyed by throwing them into a cup of water. When the ma-

* The theory of this was briefly explained in Chapter II dealing with the crystalline structure of metals.

terial has been, in a certain suitable manner, subsequently returned to room temperature in the case of iron, or crystallized by evaporation of the water in the case of sugar its new structure will be far more affected by the process adopted for developing it from the solution, be it solid or liquid, than by its life history previous to its entrance into the state of solution, and may be entirely independent of this previous history. It will be shown later that in practically all heat treatment it is necessary to heat the metal through the "upper critical point," and it will also appear at that time that this "point" represents the temperature range at which the entire metal passes into a state of solid solution. This is the first of two factors lying at the foundation of all heat treatment, and its importance lies in the circumstance that it provides a means for "wiping the slate clean" by doing away with all, or at least most, of the previous structure of the metal, and thus permits building up the new and desirable structure. The second factor is the change in the crystalline structure of the material expressed by the molecular rearrangement within the crystals, which partly covers the allotropic phenomena and also the rearrangement of the grains. There is every reason to believe that concomitant modifications of the intercrystalline cement take place and powerfully affect the resulting properties of the metal, but our knowledge of this is too scant as yet to warrant any statement as to the nature of these variations.

An attempt will now be made to give an insight into what may be called the secret of discovering the proper method of heat treating a ferrous alloy, and it is desired to lay emphasis on the statement that this chapter has not been written with the view of teaching the art of heat treatment to those who expect to practice it, but merely to explain its fundamental principles to engineers, who, in the course of their work, have to deal with heat-treated products or specify them for mechanical constructions.

Critical Points

It has been found that in cooling such iron alloys as the majority of steels, the cooling proceeds for a while so that as the temperature of the piece falls off the cooling is gradually retarded. When, however, a certain point is reached the piece not only stops losing in temperature, but under certain conditions actually appears to get hotter. Then after an interval the fall of temperature is resumed, only to be stopped again, and perhaps even a third time. On heating a steel bar the phenomenon is reversed. With the addition of heat to the piece it becomes gradually hotter and hotter, then more or less suddenly it stops gaining in temperature—and under favorable conditions may even lose—and this phenomenon may occur once, twice, or even three times as the temperature of the piece rises.

Mechanical engineers are familiar with a somewhat similar phenomenon: In heating water, when it reaches the boiling tem-

perature for a given pressure it begins to absorb heat without change in temperature. In the case of water this is called the "latent-heat absorption;" we know now, however, that this heat is engaged in doing internal work, namely, pushing the molecules of water apart until they are drawn away from each other so far that the water is converted into steam. In other words, heat during the so-called latent absorption stage is employed in effecting an internal rearrangement of the particles in the mass of water that re-

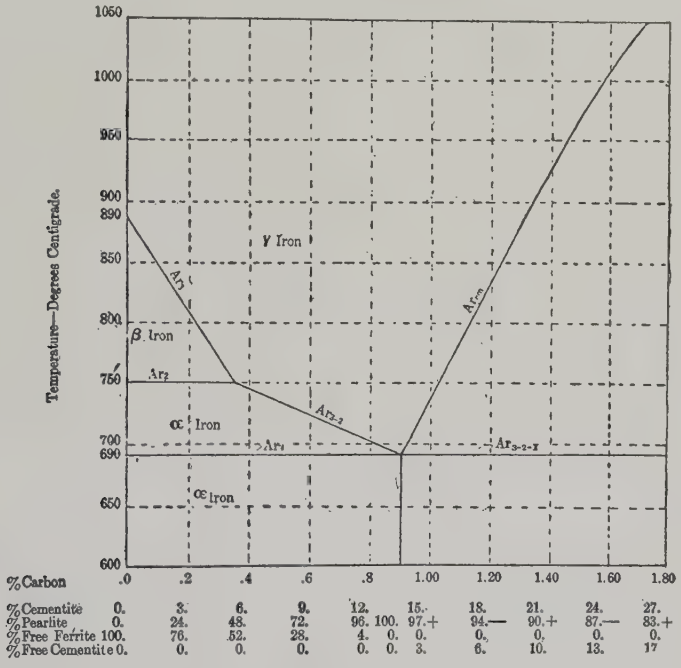


FIG. 23 DIAGRAM SHOWING POSITION OF THE CRITICAL RANGES AND THE RELATION OF THE CARBON CONTENT TO THAT OF PEARLITE, FERRITE, AND CEMENTITE

(Reproduced from The Making, Shaping, and Treating of Steel, J. M. Camp and C. B. Francis, 2nd ed., by courtesy of the Carnegie Steel Company, Pittsburgh, Pa., publishers.)

sults in its vaporization. Conversely, when steam is condensed to water of the same temperature, a large amount of heat is evolved due of an inverse rearrangement of the molecular structure of the mass.

Exactly the same thing occurs in the case of steel, though in not quite so simple a manner. To show this, we may consider the case of a low-carbon steel, such as one containing 0.2 per cent carbon, slowly cooled from the molten condition to atmospheric temperature. This case has already been discussed to a certain extent in Chapter I, p. 25, and the line yx to represent it was drawn on the con-

stitutional diagram of the iron-carbon system, Fig. 16, on the previous page. When the metal is slowly cooled from the molten condition to atmospheric temperature, it would appear that at the start we have a liquid solution of iron and carbide of iron (at least we assume so), and that at a certain point solidification of the mass occurs. The modern theory is that iron solidifies as delta iron (body-centered cubic lattice) and inverts at 1410 deg. cent. or thereabouts to the gamma variety, at which time a solid solution of gamma iron and carbide of iron is formed, called austenite. The range within which this solution is stable lies between the point where *yx* crosses *AE* and the point where it crosses *GI*. Within that range the entire metal is solid and is a mixture of austenite and gamma iron.

When the metal cools down to the temperature corresponding to the point where *yx* crosses *GI* (about 840 deg. cent.), a change occurs in its structure in that some of the gamma iron is deposited out in the form of beta iron, while the rest remains in the form of austenite. The conversion of gamma iron into beta iron is accompanied by a rearrangement of the atoms within the crystals of the metal (explained in detail in Chapter II), and is accompanied by a certain evolution of heat which either stops the cooling or may even result in a reheating of the mass called "recalescence." The reverse process occurs in heating the metal, when at certain temperatures the rise of temperature of the metal stops notwithstanding the fact that additional heat is being supplied to the metal ("decalescence").

As the cooling of the mass, which consists now of beta iron and austenite, proceeds, a temperature is reached indicated by the line *MI*. This is the lower limit at which beta iron can exist, and when this is reached a new change occurs, the beta iron being converted into alpha iron, which results in a further evolution of heat and is another instance where the continuing loss of temperature from the metal through convection, conduction, and radiation does not show on the thermometer.

Below the line *MI* no more beta iron can exist, so that in the section between *MI* and *PS* we have a mixture of gamma-iron solid solution with a steadily increasing content of crystals of alpha iron. As far as we know, alpha iron is the last allotropic modification of iron and is stable at all temperatures below the second point of transformation. But as the iron is cooled still further and the line *PS* is passed (about 750 deg. cent.), the gamma-iron solid solution is transformed into the eutectic mixture of alpha iron and cementite, the latter forming pearlite, so that ultimately the metal consists of alpha iron and pearlite. The transformation from gamma-iron solid solution into the new pearlitic structure is again accompanied by the evolution of heat.

We thus see that in the case of a low-carbon steel, such as a 0.20 per cent one, subjected to slow cooling there are three transformations accompanied by evolutions of heat: The first, called Ar_3,

occurs when gamma iron breaks down to beta iron, the second, Ar_2, when beta iron breaks down to alpha iron (the existence of this point is doubted by some investigators), and the third, Ar_1, when austenite passes into pearlite.

The process may be reversed and we may take a pearlitic steel, say, at room temperature and reheat it, in which event the first step will be the transforming of the pearlite into austenite, the second, alpha iron into beta iron, and so on, each transformation being accompanied by an absorption of heat and hence a retarded rise in temperature or possibly even a fall in temperature. We shall then have three points each way which are called Ar_1, Ar_2, Ar_3 and Ac_1, Ac_2, Ac_3, the letters "r" and "c" standing for the French words "refroidissement," meaning cooling, and "chauffage," meaning heating. The critical points Ar and Ac do not occur at exactly the same temperature, Ac being generally situated some 20 to 40 deg. higher than Ar. Some doubt, however, has been thrown on the precision of measurements which have given this result. Such measurements are very difficult to make, and moreover it should be clearly borne in mind that what we refer to as "critical points" are not really points at all, the allotropic transformations to which their existence is due being not instantaneous phenomena but processes taking place throughout the mass of metal, and therefore requiring a certain amount of time between their beginning and end. Various investigators have used temperature records taken at different stages of the process, so that in comparing published results it is necessary to ascertain the method of measurement. Moreover the position of the critical points is affected by such factors as speed of heating or cooling and temperature from which cooling begins. The mechanical engineer, however, is not likely to have to deal with such refinements of the practice of determination of the critical points of steel.

In the above discussion of the critical points of steel we have been dealing with very low-carbon steel, because in such steels the occurrence of the critical points is spaced so as to make them more clearly distinguishable. As the amount of carbon rises the point A_3 is gradually lowered until it merges with A_2. It may then be denoted as $A_{3\cdot2}$ (cp. line *zw* in Fig. 16 referred to above). As the carbon increases still further and reaches the euctectoid-steel proportions (0.89 per cent) there appears to be only one point, all of the points being merged into it. This may be denoted as $A_{3\cdot2\cdot1}$. Finally, in hypereutectoid steel there is also apparently only one critical point, denoted at times by A_{cm}, where "cm" stands for cementite. This point is rather difficult to detect.

A very comprehensive set of determinations of the critical points of iron and steel was made by Carpenter and Keeling. Their results are tabulated on page 168 of the Metallography and Heat Treatment of Iron and Steel by Prof. Albert Sauveur of Harvard University, 2nd edition, 1916. The table includes the critical

points occurring during the solidification period of the various steels and irons investigated, these having a carbon content ranging from 0.01 to 4.50 per cent.

As has been stated above, the cause of the appearance of the various critical points lies in the internal transformations which take place at the given temperatures, and these transformations may be either from gamma to beta to alpha iron or vice versa, or from austenite to pearlite or vice versa. It has been shown that these transformations are accompanied by the evolution or absorption of heat, depending on the direction of the reaction, i.e., whether the transformation takes place during the cooling of the piece or the heating thereof. It has been found that the rearrangements of molecules which accompany such transformations have effects other than the evolution or absorption of heat and that they affect other properties of the materials. Among the properties thus affected is, e.g., dilatation. Taking steels with a carbon content below 0.35, i.e., those having at least two points clearly distinguishable and possibly three, the following is found: At Ar_3 the metal which has been contracting, as is usual with bodies undergoing cooling, begins suddenly to expand, the dilatation amounting to over $^1/_{1000}$ of its length. This dilatation is immediately followed again by a normal contraction. Harbord and Hall, in describing the operation of a Morgan Construction Co. continuous bar mill state: "The bars, which are in lengths up to 300 ft., show the point of recalescence in a very clear manner, contracting rapidly at first, the contraction then gradually decreasing till it ceases entirely, and in a few seconds the bars begin to lengthen, slowly at first and then more rapidly; this soon ceases, and the final contraction sets in. The expansion while cooling often amounts to 2 or 3 in. on bars over 200 ft. long, and the movement is sufficiently rapid to be easily followed by the eye." (The Metallurgy of Steel, F. W. Harbord and J. W. Hall, 7th ed., 1923, vol. 2, p. 375.)

As the point Ar_3 marks also a passage from gamma to beta iron, it would appear that the latter is less dense. The electrical conductivity also changes, in that above Ar_3 the metal has a very high electrical resistance, which decreases only very slowly until Ar_3 is reached, and then begins to decrease rapidly. There are several other changes of lesser importance. The changes at Ac_3 are practically the reverse of those at Ar_3. The changes at Ar_2 are less sharply noticeable, with some exceptions, however. Dilatation does not seem to take place at all, or if it does, it is very slight. There is, however, a very striking change in magnetic properties in that above Ar_2 steel is not magnetic, but in passing through Ar_2 it suddenly becomes strongly paramagnetic. In steels of a higher carbon content, namely, from 0.35 to 0.89 per cent, the points A_3 and A_2 gradually merge, the metal passing through a joint point $Ar_{3\cdot2}$ or $Ac_{3\cdot2}$, at which there occurs a marked dilatation, a sudden decrease of electrical resistance, and a gain of magnetism.

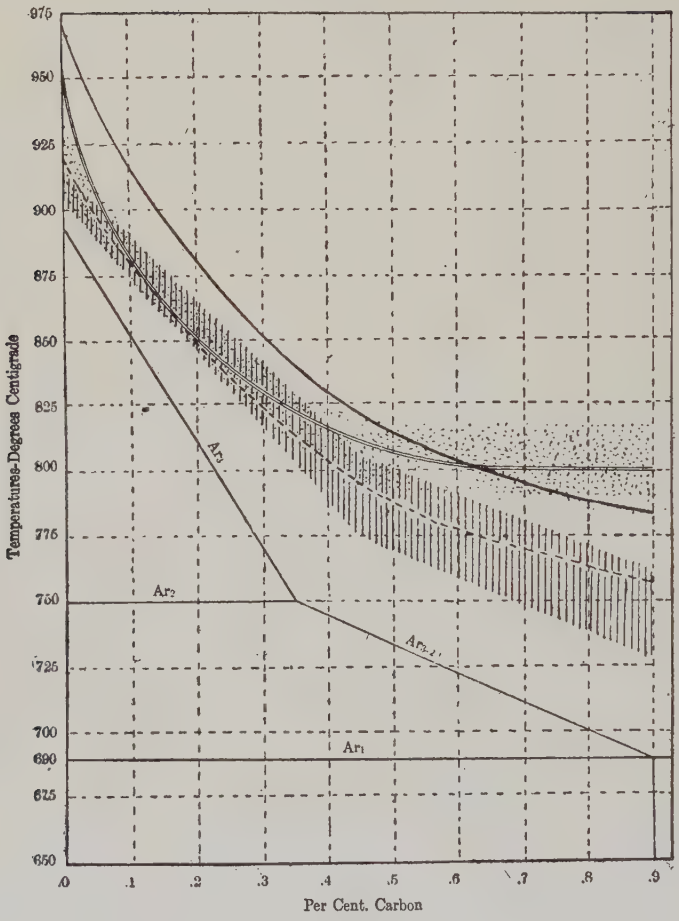
As regards the A_2 point, Kotaro Honda[2] claims that it is not a change of phase, but is due to the increase of the rotational energy about the magnetic axis of the iron atoms. This energy is a definite function of the temperature and affects the specific heat of iron by increasing it. Hence this energy is absorbed during heating and evolved during cooling as a heat effect. He states, in fact, that even above the A_2 point the intensity of magnetization is not absolute zero and can be measured by specially sensitive apparatus such as a torsion balance. Under this view beta iron would have to be excluded as an independent phase.

At Ar_1, which occurs as a separate point in steels containing up to 0.89 per cent carbon, the transformation is from austenite to pearlite. At this point the following sudden changes in properties are noted: (1) A dilatation takes place which increases with the carbon content, reaching a maximum with 0.85 per cent carbon; (2) Increased magnetism takes place for all steels on cooling through this point; (3) A marked decrease in electrical resistance is also noted on cooling through this range; (4) Below this point iron loses entirely its power to dissolve carbon.

We come now to the application of the information given above on the critical points of steel to practical problems. Such problems may be of several different kinds. We may have a casting that the microscope and other investigations show to be coarsely crystallized, hard in spots, and therefore difficult to machine, or of undesirable structure in other ways. The problem is then to find a process which will give the metal softness and change its structure generally in such a way as to endow it with high strength, good elastic limit, and reasonable ductility. The problem may be also that of increasing the hardness of a material instead of reducing it. Then again, particularly with alloy steels, it may be necessary to give the steel a structure at which this particular metal possesses its best properties, the matter of the degree of hardness being then more or less secondary. It may also happen that in the process of casting, rolling, forging, or other treatment strains may develop in the metal, and it may be necessary to remove these strains. It should be clearly understood here that the above does not exhaust all the problems in the solution of which resort is made to heat treatment.

We may start with the process called "annealing," which may be defined as heat treatment followed by relatively slow cooling, as in an oven. A modification of annealing called "normalizing" consists of heat treatment followed by an intermediate cooling operation, as in room temperature. Both annealing and normalizing consist of three operations: (1) heating the steel; (2) keeping its temperature constant at the annealing temperature for a certain period of time; and (3) cooling it from the annealing to atmospheric temperature.

As to heating, it should be such as to permit the metal to start



Legend.

==========	Sauveur (for treating forgings).
⁘⁘⁘⁘⁘	American Society for Testing Materials.
∥∥∥∥∥	Bullens (for annealing and hardening).
------	Stead's Lower Curve (for refining and hardening).
——	Stead's Upper Curve (for annealing and normalizing).

FIG. 24 ANNEALING (AND HARDENING) RANGES SHOWING APPROXIMATELY THE TEMPERATURES RECOMMENDED BY DIFFERENT AUTHORITIES

(Reproduced from The Making, Shaping, and Treating Steel, J. M. Camp and C. B. Francis, 2nd ed., by courtesy of Carnegie Steel Company, Pittsburgh, Pa., publishers.)

with what might be called a "clean slate" in reference to its structure. When the metal is chilled from casting, be it in a sand mold or ingot mold, or when it has undergone cold working, a certain structure is imparted to it as the result of the mechanical strains or the various rates of cooling. This structure may be uniform throughout the piece or different in various parts; for example, in an ingot the structure of the outer shell usually differs quite materially from that of the core. The only way to obtain a uniform structure seems to be to obliterate all former structures, no matter what they may be, and to bring the piece to a uniform "base" structure from which, by a proper method of rebuilding, a new structure can be obtained such as will give the metal the desired qualities. In the case of carbon steels the proper procedure is to go back to the stage where the steel consisted entirely, let us say, of austenite, which is above the upper critical point Ac_3 in the case of low-carbon steel (0.35 per cent carbon and less), $Ac_{3\cdot2}$ in the case of steel containing from 0.35 to 0.9 carbon, and $Ac_{3\cdot2\cdot1}$ in hypereutectoid steels.

If the steel is heated below this range no structural change takes place. (There are, however, a few exceptions to this, such as the case of cold-worked hypoeutectoid steel when the distorted ferrite may be restored to its normal crystalline structure by heating slightly below the critical range, as cited by Prof. Albert Sauveur in The Metallography and Heat Treatment of Iron and Steel, 2nd edition, 1916, p. 232.) On the other hand, it is not desirable to carry the temperature of heating very much above the critical point as this tends to coarsen the ultimate structure of the metal. It is because of this that, in annealing, steel should be heated just through the critical range, which means that the temperature of the critical point should be previously ascertained. This may be done either by direct measurement of the temperatures of bars from which known quantities of heat are abstracted or to which known quantities of heat are added, or it may be done by the measurement and simultaneous recording of temperature and dilatation, valuation of electrical conductivity, magnetic properties, etc.

As regards the duration of annealing, the article should be kept at the annealing temperature long enough to be "soaked through," i.e., heated clear through to that temperature. According to the Committee on Heat Treatment of the American Society for Testing Materials, an exposure of one hour should be long enough for pieces up to 12 in. thick. It is very important that annealing should be carried on at a uniform temperature. Coming now to the question of cooling from annealing temperature, this latter depends entirely on the properties which it is desired to give to steel. Austenite cooled with great rapidity, as in quenching, generates martensite, which is extremely hard and lacks in ductility. With a cooling quite rapid but less so than quenching, sorbite is produced, which combines a considerable amount of hardness—inferior, however,

to the martensitic structure—with a certain amount of ductility and great tensile strength. A still slower cooling leads to the formation of the pearlitic structure, which is soft and highly ductile but lacks in the matter of strength. This is, however, only a general rule which is modified largely by a number of factors such as size of object, etc. A very important factor is the carbon content, as the lower the carbon content the more rapid may be the cooling from the annealing temperature without creating excessive hardness, this being obviously due to the fact that even if the carbide of iron is converted into hard martensite, this latter will be embedded in such a predominant matrix of soft ferrite that the ultimate properties of the metal will be determined by it.

A good deal of the success of the annealing operation depends on the initial structure of the metal. If the grain size in the piece is fairly good to start with, i.e., not excessively coarse, the annealing is simple. If, however, it is very bad or if the material dislocation of the structure of the metal has been produced by mechanical working, special annealing methods may have to be resorted to. The particular feature of these annealing methods is that the length during which the piece is held at the annealing temperature and which under normal conditions for pieces up to 12 in. thick need not extend beyond one hour, may in exceptionally bad cases have to be very long, running into days at times. This is only natural because rearrangement of molecules in solid matter is always a slow process and if these molecules have to travel a long path, or if the rearrangement requires a more than usual amount of displacement, a suitable length of time has to be provided. It would further appear that the greater the internal stress upon the steel, the greater is the amount of intermolecular lag or final release of this stress beyond the actual change of constituents; i.e., even though a totally new structure may be set up by the annealing, there remains for a considerable length of time a tendency of the new structure to return upon slow cooling to the stressed condition of the original, even though the constituents themselves may be those born at the new temperature. Denison K. Bullens (Steel and Its Heat Treatment, 2nd edition, 1918, p. 135) explains this by phenomena of diffusion and shows a series of interesting photographs illustrating progressive absorption of the excess ferrite between the lower and upper critical ranges.

At times overheated steel has to be refined. The success or failure of this operation depends on the size of the piece and on the degree of overheating. Small pieces may be refined by a long and thorough saturation at the ordinary annealing temperature. In the case of large sections the success of annealing is much more doubtful and although the steel in general may have after annealing a fine-grained structure, large grains or "islands" may persist here and there, and under certain conditions cause trouble. If the steel has been very badly overheated or burned it is practically impossible

to bring it back to a good structure. Bullens, in his work quoted above, p. 147 (Fig. 130), shows a photograph of a 10-in. shaft which was badly overheated and then underwent eight annealings at various temperatures, totaling some 200 hr. of heat saturation. Even after such repeated heating and cooling the arrangement of the ferrite of the originally overheated metal was not eliminated entirely.

Where annealing in an open furnace may affect the surface of the metal, box annealing is used, the articles being placed in a box which is then placed in the furnace. Originally the boxes were made of cast iron or of steel sheets riveted together, and were often lined with refractory material. Some of the disadvantages of these boxes were their comparatively short life on account of scaling and their tendency to warp, which often made tight adherence between box and cover uncertain. Of late special alloys, usually of the type with a high chromium content, have been employed for annealing boxes. Such alloys do not scale and have less tendency to warp.

Electric annealing is also coming into extensive use. Three methods of electric annealing are possible. In the one used most commonly the article to be annealed is placed in the furnace, usually of the muffle type, and the latter heated by passing electric current through resistance elements, such as chromel or nichrome wire, wound around the muffle inside or outside. The great advantage of such electric-furnace annealing is that there are no furnace gases to come in touch with the object being annealed, the temperature can be controlled with great precision, and the objects are conveniently handled. The second method of electric annealing, used chiefly in mass production of articles of uniform cross-section and length, such as rods, tubes and sheets, is to use the article itself as the resistance element. Current is passed through it, and usually the expansion of the article is employed as an indicator of temperature.[9] This is known as the Snead process. The third method, which has not been applied commercially to any appreciable extent but which may be used under certain conditions, is by passing high-frequency current around the article and inducing eddy currents in it, thus producing the heating. Because of the high cost of high-frequency apparatus this process is not likely to be used where other processes are applicable.

Until comparatively recently many industries viewed heat-treated products with a good deal of distrust. The early automobile manufacturers, in particular, refused to use heat-treated steel. This distrust has practically disappeared and at present enormous quantities of heat-treated steels are used in automobile, locomotive, and other constructions where great reliability combined with high strength is required. The reason for this change of attitude is probably due to two factors. In the first place, there is a clearer understanding of the mechanism of heat treat-

ment, combined with a better knowledge of the temperatures at which it should be carried out. It is not enough, however, to know at what temperatures to treat a metal unless there is a certainty that these temperatures will be maintained in the heat-treating furnaces. This is the second factor that has led to the wide adoption of heat-treated steels in recent years. The development of special furnaces for heat treating, together with the development of methods of temperature control by pyrometers, has created a situation where properly heat-treated steel has become the rule rather than the exception, and where most of the guesswork has been taken out of the heat treating of steel. At the same time it should be clearly realized that even with pyrometric control and modern furnaces, heat treatment of steels is frankly not a job for amateurs but requires a considerable amount of skill and proper organization to give all the advantages which may be derived from it.

Heat Treatment of Steel Castings

A simple annealing treatment when applied to plain carbon-steel castings has, in general, very little effect on the elastic limit and tensile strength and in fact, many castings of thin section will have their elastic limit and tensile strength actually reduced by the annealing operation. But such a simple annealing treatment does produce a decided increase in ductility,[3] which results in a much greater resistance to impact stresses and also tends to produce a uniform elastic limit and tensile strength throughout the entire section of the casting. Where the design of the casting is such that quenching and drawing can be employed the heat treatment makes it possible to obtain better physical properties; but interior defects and irregularities of steel castings are very apt to make the quenching operation exceedingly dangerous as regards development of cracks, it being practically impossible to quench castings of certain design without the development of checks and cracks which may not always be apparent upon surface examination and therefore are all the more dangerous.

On the other hand, some metallurgists recommend the following treatment for steel castings.[4] The steel is first subjected to a temperature considerably above the critical range for a time long enough to permit the process of diffusion approximately to equalize the structure. The steel is then cooled slowly to a temperature just above the critical range. A rapid cooling through the critical range then supplements the effect of the previous treatment in bringing about dispersion of the ferrite. Quenching leaves the metal in a state of internal strain and reheating or drawing is necessary to eliminate this. This drawing is carried out at a temperature of 550 deg. cent. (1022 deg. fahr.). (Cp. p. 191.)

Hardening

The process of hardening is based on the structural changes de-

scribed above. As has been shown, steel of practically any structure can be changed to that of a solid solution or austenite by heating it through the upper critical range. When the steel is cooled down this austenite is converted first into martensite, then on further cooling into troostite, sorbite, and pearlite, depending on the temperature at which the process of cooling has been stopped and the rate of cooling. Now if the cooling is very gradual the steel

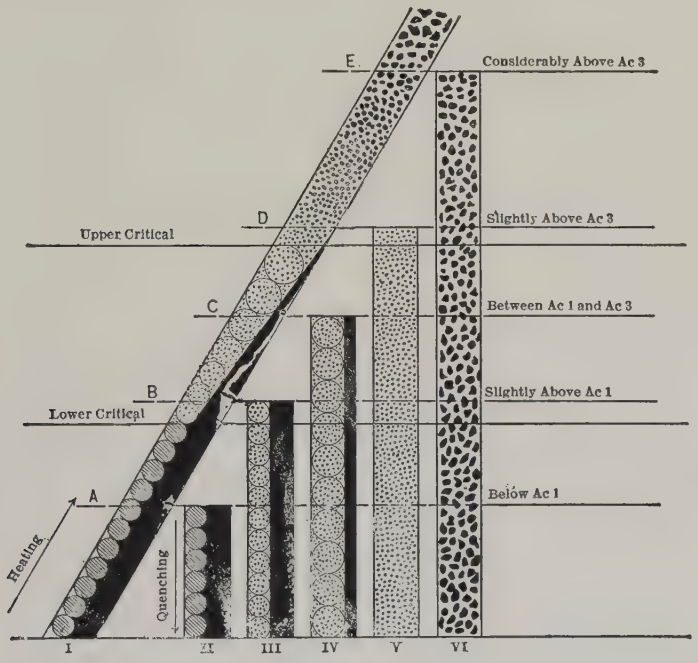


FIG. 25 CHANGES IN A 0.4 PER CENT CARBON STEEL ON HEATING AND QUENCHING

(Reproduced from Steel and Its Heat Treatment, Denison K. Bullens, by courtesy of John Wiley and Sons, New York, publishers.)

will pass through all of these stages and end with a pearlitic structure which is soft and ductile, but if it is rapid, one of the intermediary stages between austenite and pearlite may be "trapped." In the case of ordinary steel, a very rapid method of cooling called "quenching" permits trapping or stabilizing the martensitic structure, and as has been shown above, martensite is extremely hard. Hardening therefore consists of first heating a steel through the critical range and then rapidly cooling it as by quenching in a liquid capable of taking up the heat of the metal very rapidly, such as water or oil. Fig. 25 shows the changes in a 0.4 per cent carbon steel on heating and quenching.

Thus heating to a temperature *A*, under that of the lower critical range will produce no change in the original steel, which consists of pearlite (the cross-hatched circles) and ferrite (the black area). The quenching likewise will produce no change, as is illustrated by column II.

Heating to a temperature *B*, slightly over the lower critical range, will change the pearlite to the solid solution (represented by the dotted area), but without affecting the free ferrite. Quenching, column II, will therefore produce a semi-hardened steel—since the solid solution is the "hard" constituent—with a refinement of the "ground mass" (the original pearlite) only.

Heating to a temperature *C*, between the lower and upper critical ranges, will affect a progressive absorption by the solid solution of the remaining free ferrite. Quenching, column IV, will therefore produce a "harder" steel than in case III, but nevertheless without complete refinement of the steel as a whole.

Heating to a temperature *D*, slightly over the upper critical range, if prolonged for a length of time sufficient to effect complete diffusion and equalization, will entirely refine the steel, giving it the smallest grain size possible. Quenching, column V, will retain this condition and give the maximum hardness possible.

Heating to a temperature *E*, considerably over that of the upper critical range, will tend to increase the grain size; and quenching, column VI, will retain this condition and will give a more brittle steel.

As regards heating for hardening, the general rule is that it should be slow, uniform, and thorough, and carried to the lowest temperature which will give the desired results, as heating much above the critical range will produce a coarse crystallization. There is an expression, "hardening steel on a rising temperature," which simply means that the steel is heated through the critical range and cooled suddenly as soon as it passes this range. In practice it is recommended to have the quenching temperature some 20 to 50 deg. cent. above Ac_3 in hardening eutectoid and hypereutectoid steels, and above $Ac_{3\cdot2}$ in hardening hypoeutectoid steels. The actual quenching temperature depends, however, on the carbon content of the steel.

As regards quenching, it is very important that the piece treated should have a uniform temperature at the time of quenching. A piece may be heated to a uniform temperature in the furnace but so improperly handled that by the time it reaches the quenching bath one part of it will be hotter than another. This will produce a non-uniform hardening and may lead to warping or cracking of the piece. In order to give the metal a uniform temperature and also to make it possible to control this temperature, heat treaters resorted to the use of liquid heating baths, such as, for example, baths of molten lead and certain salts.

There are certain practical objections to the use of both lead and

salt baths, but they, and particularly the salt baths, have the advantage of permitting a close control of the temperature of the bath, which can be measured with a fair degree of precision by means of a simple pyrometer, and at times estimated even without a pyrometer from a knowledge of the melting point of the salt.

A recent review of the theories of the hardening of steel within the last thirty years is presented in a paper by Prof. Albert Sauveur.[15] Some of the conclusions at which the author arrives are as follows:

Austenite is a solid solution of carbon, probably in the form of the carbide Fe_3C in gamma iron.

Troostite is a solid solution of carbon, probably in the form of the carbide Fe_3C in beta iron.

Austenite always transforms into troostite—regardless of the temperature at which the transformation takes place.

Martensite is the aggregate of austenite and troostite necessarily resulting from the gradual transformation of austenite into troostite.

Troostite of eutectoid composition transforms into sorbite.

Pearlite results from the coagulation into plates of the constituents of sorbite.

Gamma iron being unstable at room temperature, austenite, on reheating, tempers into troostite through the transformation of gamma into beta iron and the retention of the carbide in solid solution.

Although beta iron is more stable than gamma iron, troostite, on further reheating tempers into sorbite through the transformation of beta into alpha iron and the rejection of the cementite.

Austenite is harder than gamma iron because it is a solid solution, it being well known that solid solutions are generally harder than the solvent.

Troostite is harder than austenite, possibly because beta iron is harder than alpha iron; also possibly because of the presence of troostite of submicroscopic grains offering greater resistance to slip, the structure of troostite being much finer than that of austenite; because of the distortion of its crystal lattice or, again, because of the existence of severe internal strains.

The hardness of troostite increases with the percentage of carbon it contains, possibly because of increasing smaller grains.

The aggregate martensite is harder than the troostite it contains, and *a fortiori* harder than the austenite because the structural arrangement of these two constituents offers greater resistance to slip than plain troostite. Its very acicular structure favors that view, as pointed out by Thompson, who writes that "the needles formed a strengthening scaffold throughout the mass."

The hardness of martensite increases with its carbon content because of the greater hardness of the troostite it contains, and possibly also because finer needles and finer grains result from the transformation of austenite containing much carbon.

Theory of Quenching Steels[5]

From the structural point of view the A_1 transformation consists of Austenite $\rightleftarrows$ pearlite, but according to Kotaro Honda, an eminent Japanese metallurgist, this shows only the result of the transformation and the change itself is in reality a stepped change, i.e., austenite $\rightleftarrows$ martensite $\rightleftarrows$ pearlite, or solid solution $\gamma \rightleftarrows$ solid solution $\beta \rightleftarrows$ Fe + Fe_3C. During a slow cooling, at the A_1 point, austenite first changes into martensite and the latter being at the high temperature changes immediately into pearlite, the result being the same as austenite to pearlite. During a very rapid cooling such as quenching the change from austenite to martensite is so far retarded that it begins to take place at below 300 deg. cent. (572 deg. fahr.), and when this change is completed the specimen is nearly at room temperature and hence a second change from martensite to pearlite cannot take place, owing to the great viscosity of the specimen at room temperature. According to this theory the perfect quenching is obtained when the first change in the stepped transformation, austenite to martensite, completely takes place, and the second change, martensite to pearlite, is completely suppressed. In the case of a less rapid cooling, the second change progresses partially, resulting in a martensitic structure mixed with pearlite (troostite).

Other investigations have indicated that there are two kinds of martensite, α and β, the A_1 transformation during cooling taking place in the order austenite $\longrightarrow$ β martensite $\longrightarrow$ α martensite $\longrightarrow$ pearlite. Both martensites have a body-centered cubic lattice with regard to iron atoms and the difference between them probably consists in the mode of distribution of carbon atoms within the space lattice of iron atoms. (Cp. p. 37.)

In imperfect quenching, as referred to above, where the slower rate of cooling is used, the first change (from martensite) begins to occur at about 450 deg. cent. (842 deg. fahr.). When it is completed the specimen is still at a high temperature and hence a second change occurs before it is cooled at room temperature. This change consists of the precipitation of cementite as fine colloidal particles from a martensitic solid solution; this structure is usually called troostite. If the cooling is still slower the formation of troostite takes place at a higher temperature and if the further cooling at room temperatures is conducted very slowly, troostitic particles coagulate to some extent by virtue of the surface tension and the structure called sorbite is obtained.

In practice it is usual to obtain troostite and sorbite by tempering quenched steels. The martensite when left to itself at room temperature scarcely changes into pearlite, owing to the high viscosity of the material at this temperature, but when it is raised to 300 to 400 deg. cent. the martensite slowly changes into troostite by the decomposition of fine cementite particles. By raising the reheating temperature to from 500 to 600 for a certain interval of time, the

coagulation of troostite particles goes on to such a degree that the structure becomes sorbitic.

The Quenching Bath

A liquid is selected for a quenching bath on the basis of its ability to absorb heat from the piece at the desired rate.[14] This latter depends in the first place upon the specific heat of the liquid, also on its conductivity and viscosity. The volatility of the liquid may be of importance because it indicates the temperature at which a vapor envelop may form around the steel that will interfere with the flow of heat from the metal to the liquid. For further data as to the behavior of the various liquids, the reader is referred to the paper, Factors in Hardening Tool Steel, by John A. Mathews and Howard J. Stagg, Trans. A.S.M.E., vol. 36, 1914, pp. 845–872. On the whole, water is the fastest-cooling medium. The most drastic cooling is obtained when a stream of water is directed on to the piece, provided the volume and pressure of the stream are sufficient to prevent the formation of a steam envelope around the piece. Dipping in a tank of water is somewhat slower than quenching by water spray. Oils are a slower-cooling medium, the various oils acting in different ways. (A list of eleven oils with their quenching factors is given in Bullens' Steel and Its Heat Treatment, p. 173.) Oil quenching is sometimes referred to as "oil tempering," while "hardening" is restricted to quenching in water only.

Brine is used only for certain particular purposes, such as hardening files, for which an extremely hard surface is required. Unless the steel has been most carefully heated and is of the proper chemical composition, quenching in brine is almost certain to crack it, particularly in the case of large sections.

Where pieces, such as large forgings, are of such a size and chemical composition that direct quenching in water may induce excessive stresses, a bath is used consisting of a tank in which a certain volume of oil is floating upon cold water. The forging heated to the proper temperature is dipped into the oil for a few seconds and then pushed down into the water. The quenching therefore proceeds in two stages and may be controlled to some extent, while the rapidity of cooling in water is somewhat delayed by the film of oil which forms on the surface of the steel. When small tools are treated in this way they are simply plunged through the oil into the water, the thickness of the oil layer regulating the relative importance of the two stages of cooling.

While hardening steel by quenching in oil and water is very extensively practiced, there is a wide gap in the range of quenching power between water and commercial quenching oils. This may be bridged partly by using water heated to a suitable temperature, but such a procedure is not reliable inasmuch as the cooling rate rapidly changes with small variations in the water temperature as the boiling point is approached. Another method is to use an

emulsion of oil and water. It has been found, however, that the quenching effect of the emulsion follows a more complicated law than merely the ratio of the oil and water contained therein, and the presence of air bubbles affects the results very materially.

It would appear, however, that glycerin-water solutions[6] of various concentrations give the desired range of cooling rates, and, in addition, that at low temperatures, a glycerin solution cools over twice as fast as oil; hence it is possible to select a glycerin solution which will harden no deeper than oil and yet cool through the lower temperature range more rapidly.

While glycerin is quite expensive ($1.10 per gal. for crude glycerin in bulk), this is offset by the fact that it does not decompose on heating as do oils. It is not chemically active under conditions encountered in heat treatment, and does not give off fumes to an objectionable degree.

One of the interesting things found in work on glycerin-water quenching solutions was that the cooling rate of the center where the center has cooled to 620 deg. cent. (1112 deg. fahr.) from 800 deg. cent. (1472 deg. fahr.) decreases continuously with the addition of glycerin to water, the decrease being more rapid for high percentages of glycerin than for low.

It is very important to maintain the quenching bath at the proper temperature, as the rapidity of quenching depends on the temperature of the bath. In the case of water, 50 deg. fahr. difference of temperature make a big difference in quenching results. Where a bath is used continuously, provision has to be made to cool it.

One of the greatest dangers in hardening and subsequent quenching is the possibility of cracking and warping of the piece being treated. This is due to two factors. In the first place, all metals expand on heating and contract on cooling, and hence will rapidly contract in quenching. However, this is not the only factor tending to produce stresses. In the discussion of the critical ranges it was indicated that the formation of austenite takes place with a decrease in volume, while the degeneration of the austenite to martensite on cooling through the same range is accompanied by an increase in volume, and there is a second increase in volume as martensite breaks down into pearlite. If a large piece of steel is quenched rapidly the outer section will be held in the hardened condition, say, martensite, while the interior, being cooled less rapidly, will pass to a lower stage, such as pearlite, and will therefore increase in volume, the result being a stress from the inside against the outer shell. This stress may be extremely high; for example, heavy locomotive-axle forgings have been known to burst open with a report like a pistol shot upon the removal from the oil hardening bath.

Another explanation of quenching cracks is given by Kotaro Honda,[7] who points out, however, that in quenching, cracks usually occur in 10 to 15 sec. after quenching in water, and that

furthermore cracks do not occur unless the quenching temperature exceeds 800 deg. cent. He believes, therefore, that the cracks occur only when the quenching temperature exceeds the Ac_1 or Ar_1 points, and that therefore they must have some connection with the A_1 transformation. He found from quenching experiments that in the outer portion where cooling is very rapid, not only the second change of the A_1 transformation martensite $\longrightarrow$ pearlite is stopped but also the first change austenite $\longrightarrow$ martensite is partly arrested, so that this portion contains a certain amount of austenite intermingled with martensite. In the inner portion the rate of cooling is not so rapid and hence the austenite is transformed into martensite more completely. Because of this the martensitic expansion in the central portion exerts a tension in the outside portion and this tension causes cracking.

In order to reduce these internal stresses heavy forgings of large diameters, axles, shafts, etc., are drilled or hollow-bored so that the quenching solution can remove the heat from both the inner and outer part of the axles at the same time and the internal pressure may be relieved and also distributed between two surfaces instead of one. Hollow-bored axles should be quenched vertically whenever possible, and provision should be made for a constant flow of the quenching liquid through the bore.

Warping may be due either to the same causes that produce cracking or to unequal contraction and expansion of the various parts of the piece because of incorrect heating or improper quenching.

At times (chiefly with low- and medium-carbon steels) double quenching is used in order to raise the elastic limit and tensile strength without diminishing the ductility. This is usually done by first quenching from a temperature 100 to 200 deg. above the critical range, then reheating to just enough over the critical range to obtain the degree of hardness required, and quenching again.

Annealing of Cold-Worked Metal[8]

As explained in the chapter on the Crystalline Structure of Metal, the present theory is that such metals as steel consist of crystals having certain more or less definite shapes, the space between them being filled by an amorphous material which may be called the "intercrystalline cement." It is further presumed that when metals are subjected to deformation below the annealing temperature there occurs a slip or shear of mobile layers at the internal surfaces. Furthermore, these latter are supposed to retain their mobility for only a very brief period. Then they solidify in a vitreous (glasslike), amorphous state and this vitreous mass is hard and to a certain extent brittle, like glass. The result is a hardening and embrittlement of the metal.

Now it has been found that metals which have been hardened by cold work can have this hardness removed by being heated to a suitable temperature. It would appear that heating restores the

crystalline state of the metal which has been made amorphous by the cold work. Not only this, but it would appear that where during the cold work grains of metal have been deformed, the heating leads to the distorted grain structure being replaced by new grains. It also appears that these new grains are essentially of such a character that their diameters are approximately the same in all directions (such grains are called "equiaxed"). This process of restoring the softness and ductility of cold-worked metal is also called annealing and the process occurring in the metal is referred to as "recrystallization." The recrystallization temperatures differ from the temperatures used in annealing to remove hardness produced by excessively quick chilling, and, for example, for iron are of the order of a minimum of 450 deg. cent., although usually a higher temperature is employed. Excessively high temperature will produce grains which are too large. For further information on cold work and the effect of annealing, see references in Chapter II, pages 50 and 51.

Tempering

The result of heating a piece of steel through the upper critical range and then quenching it in water is that the steel becomes hard. This is due, as stated above, to the fact that the degeneration of austenite has been arrested at the martensitic stage. Unfortunately, however, such hardness is often accompanied by brittleness and also by what are known as hardening strains, which latter may be so high with certain types of steel as to cause the piece to shatter, and which always constitute a source of weakness in the material.

As a rule, as for example in tool steels, it is desirable to have only a reasonable degree of hardness accompanied by high mechanical strength, rather than a mechanically weak but extremely hard structure. To obtain the former, heat is applied in a certain manner, and this removes more or less the hardening stresses and converts to the desired degree the hard and brittle martensitic structure into a softer and tougher troostitic or sorbitic structure. Such an application of heat as will result in the establishment of a troostitic structure is called "tempering." Troostite begins to form at about 400 deg. fahr. or a little lower, and as the tempering temperature is increased the amount of troostite increases, until at about 750 deg. it begins to change into sorbite.

The old blacksmith, who in his way was an adept at tempering, had to work without thermometers or pyrometers. He knew, however, that if a piece of hardened steel was cleaned with emery cloth or a fine file and then heated slowly in the air, characteristic "temper colors" would appear on the cleaned surface, beginning with a faint yellow at about 420 deg. fahr., and gradually passing through brown and purple into a greenish blue. When the desired color was reached, the blacksmith used to quench the piece to stop any further

rise of temperature, or as it was called, "to set the grain." This is, however, a very crude process, as the color method is at best only a rough way to judge of the temperature, and as it indicates little beyond the surface temperature—and even at that does not insure that the temperature over the entire surface is uniform. The quenching from a given color is also apt to make trouble, as too much reliance has to be placed on the personal equation of the operator.

Modern tempering is therefore done by means of so-called liquid baths, usually oil. The bath is maintained at the proper temperature determined by a thermometer, and the pieces are immersed in it, and kept until thoroughly and uniformly "soaked through with heat." If the piece is kept in the bath longer than is absolutely necessary, no harm can result as the piece cannot be overheated. It is desirable to immerse the steel into the bath when the latter is some 200 to 300 deg. below the highest temperature employed in the tempering operation, and to bring the steel tempered and the bath to the required temperature together. As a general rule, when liquid baths are employed for tempering, quenching is unnecessary.

Toughening

As has been stated above, heating to about 400 deg. fahr. or a little below it, converts the martensite into the softer and stronger troostite. A reheating (or, as it is sometimes called, "drawing") to a still higher temperature, say, 750 deg. fahr. (medium forging and higher-carbon steels), changes the troostite into sorbite (cp. p. 15), which latter is endowed with great tenacity and high elastic limit. Because of these properties sorbitic steels are called "toughened steels," and the process of producing them referred to as "toughening." This is carried out by reheating the steel (usually of the medium forging and higher-carbon grades) to some temperature above 750 deg. fahr. but below 1250 deg., as at this latter temperature sorbite is converted into pearlite. The higher the toughening temperature, the lower the tensile strength and elastic limit, and the greater the ductility and dynamic endurance, which simply means that the steel approaches more nearly the properties of pearlitic steel. The effects of temperature on ductility are more complicated, and are expressed by Denison K. Bullens (p. 203) as follows: "Through the sorbitic stage at least, each increment of decrease in tensile strength and elastic limit is associated with, and counterbalanced by, an increase in the reduction of area and elongation. This combination of static strength and ductility is further almost directly proportional to the toughening temperature."

It may be stated that we are unquestionably only at the beginning of a proper comprehension of the mechanism of heat treatment and of the advantages that may be derived there-

from. It is stated on good authority that at the works of one of the largest automobile manufacturers in the country intensive work is being done to determine whether alloy steels for certain parts might not be replaced, without impairing the strength of the parts, by carbon steels, provided these latter were given as careful heat treatment as alloy steels usually get. If this can be done, new and vast possibilities open up before the mechanical and metallurgical engineer.

While very great progress in the art of heat treatment has been already made, there is scarcely any doubt that we are only at the beginning of a great development. The steels that are made today have a tensile strength ranging from about 75,000 lb. to perhaps as high as 250,000 lb. per sq. in. Theoretically there is no reason why steels even of the common carbon variety should not have a tensile strength at least ten times as high. It is the arrangement of molecules or crystals (we do not know which) that produces the present or ultimate strength of steel, and we have already found that at least some progress in this direction can be achieved by the various operations which classify generally as heat treatment.

The work of engineers of the General Electric Co. in developing tungsten wire for incandescent-lamp filaments and the very recent work of the engineers of the Westinghouse Electric & Manufacturing Co. in producing pure chromium wire, have shown that a combination heat treatment with mechanical working at elevated temperatures produces results which heat treatment alone is incapable of producing. Roughly speaking, something of the same character is done in steel as well, and, for example, ordinary rolling, such as that used in the manufacture of structural steel, rails, and hot rolled plates and sheets is nothing but a combination of mechanical working at high temperature and heat treating. Whether swaging such as is used in the production of tungsten wire has a different effect on the ultimate physical properties of metals from rolling, we do not know. We do know, for example, that blooming, which is the rolling of large ingots, produces substantially the same results as does cogging of similar ingots under a hammer. There is, however, a substantial difference between the rapid blow of the swaging process and the comparatively slow blow of the cogging hammer, and furthermore, in relation to the cross-section of the swaged wire the blow of the light swaging hammers is very much more powerful than that of the heavy cogging hammer for the cross-section of the ingot being cogged. There is therefore every reason to believe that really important progress in the way of improvement of mechanical properties of metals is in sight.

As an illustration of the progress of heat treatment being made all the time, may be mentioned the recently discovered possibility of improvement of heat treating certain chromium-nickel steels extensively used in the automotive industry.[16]

The quenching temperature is generally determined in relation

to the critical point in heating. This method is justified, however, only in cases where the Ac and Ar points are close together. A large number of steels, such as the chromium-nickel steels of the automotive industries, show a decided depression of the critical point upon cooling, with the difference between the two critical points as high as 700 deg. fahr. In actual practice, considerable difficulty was experienced in hardening hollow rolls and rings having a wall thickness of approximately 5 to 6 in. Many of the rolls cracked when quenched in oil. An investigation was made and it was found that when the quenching temperatures were gradually decreased from 1525 to 840 deg. fahr. there was a steady increase in elongation and in reduction of area, while the Brinell hardness and tensile strength remained fairly constant (until a temperature of 750 deg. fahr. was reached). At this latter temperature the critical point on cooling was reached, causing a drop in hardness and in tensile strength. The toughness figures at this point have also dropped due to an uneven hardness. Due to this effect the metal cannot stretch equally over its whole length, producing fracture with less elongation than that which would correspond to its tensile strength.

A different quenching process therefore has to be employed in which the quenching temperature is dropped from the usual one of 1525 or 1550 deg. fahr. to a temperature in the neighborhood of the thermal critical point of cooling; with such quenching it is possible to obtain the maximum hardness and tensile strength that the steel is capable of giving, combined with 12 to 13 per cent elongation, by which hardening cracks are eliminated. This also affords the possibility of quenching articles of slender shape at a temperature below visible red when the steel is stiff enough not to bend when handled.

In a good many cases what might be called invisible or rather unintentional heat treatment is involved. At times this may be beneficial. At other times it may lead to troubles which are often ascribed to anything but this unintentional heat treatment, and whenever a part of a machine which at any time in its history has passed through a temperature range that might cause a change in its physical characteristics gives trouble, it might be well for an engineer to consider what effect the heating and cooling involved may have had. The following instance is cited as an illustration thereof.

Malleable-iron castings[17] become frequently brittle as a result of hot-dip galvanizing. An extensive investigation carried out by the metallurgical department of the Ohio Brass Company has shown that the galvanizing itself has nothing to do with the creation of this brittleness, and that it is the heating to a temperature of about 860 deg. fahr. (460 deg. cent.) and the rapid cooling rate that are the important factors. Further research has shown that there is a well-defined range of temperatures (570–1120 deg. fahr. or 300 to 500 deg. cent.), quenching from which produces brittle

metal. On the other hand, it has been found that the impact values obtained on quenching from the zone 1100 to 1380 deg. fahr. (600 to 750 deg. cent.) are unusually high—higher than in untreated malleable iron. A method has therefore been developed in which the iron is heated to about 1200 deg. fahr. (650 deg. cent.) and quickly cooled, preferably by quenching in water. It has even been found that this treatment permits reclaiming any iron preciously embrittled by galvanizing.

Heat Treating Cast Iron

Heat treating as applied to cast iron, which means practically exclusively annealing, is used (1) to relieve internal strains set up by primary crystallization produced during the solidification of the iron, and (2) to soften the castings by eliminating the surplus combined carbon which appears as hard spots and white edges, making impossible a normal working in the machine shop. A gray-iron casting would readily be machinable in all sections if its silicon content could be held within the required close limits. Due to cupola conditions and other influences, however, it is likely to become too low, and that causes hard spots in castings. Heat treatment may be resorted to for the purpose of eliminating these hard spots.[20]

Tests have shown that the maximum amount of graphitic carbon in either high- or low-silicon irons is precipitated in heating the piece for about half an hour at 1400 deg. fahr. Very little increase is obtained by heating longer than half an hour, and a shorter period does not appear to be sufficient either. Silicon does not have a marked effect on graphitization. Metallographic examination shows that in heat-treated pieces graphite particles are more numerous and larger, and that the graphitization produced is more complete at the center of the piece than at the edges.

Annealing gray-cast-iron pistons is said to result[21] in an increase in machinability, a 30 to 40 per cent decrease in strength properties and hardness and an 8 to 10 per cent decrease in modulus of elasticity, a slight decrease in maximum deflection under transverse load, and a 10 per cent decrease in allowable working stresses for the same deformation.

Case-Hardening

It is quite frequently necessary to produce steel parts with a hard surface but a comparatively soft interior so as to have a material capable of withstanding wear by friction and yet resilient enough to stand shocks. At times also it is desired to produce as cheaply as possible parts having a hard surface without much regard to the character of the interior. In either case the articles are made of soft steel or wrought iron and then by various means given a hard surface ("case"). The most common method of doing this is by increasing the carbon content of the surface and

then heat-treating the article in a manner to impart to it the desired hardness. In this way an article is obtained which is to all practical purposes mild steel inside and tool steel or the like on the outside. The art is very old and was practiced in the production of files at least as early as the ninth century.

The most common process is to imbed the article into what is known as a carbonizing mixture in such a manner as to prevent access of air to it and then heat it to a very high temperature—of the order of 1000 to 1100 deg. cent. (1832 to 2012 deg. fahr.)—for a certain time, depending on the desired depth of the case. Upon removal from the carbonizing bath the article is given proper heat treatment when necessary.

The carburizers may be solid, liquid, or gaseous. The simplest solid carburizer is good charcoal, and it has been found that hardwood charcoal acts better than soft wood. Other forms of carbon may be used and even diamonds have been so employed, only experimentally, of course. The carbon is often mixed with various salts such as barium carbonate (Carron's mixture), sodium chloride, etc. The article is placed in a so-called "carburizing box," which is usually as small as possible, and closely packed with the carburizing material. The cover is then closed and luted with clay. This latter is important. It is by no means clear yet just how the carbon penetrates into the iron. From various experiments it would appear, however, that in carburizing there is no direct interaction between the solid carburizer and the iron, and that it is the gases, particularly carbon monoxide, evolved during carburization that do the work. Obviously, the carburizing would fail entirely or be substantially interfered with if the gases were allowed to escape from the carburizing box.

Liquid carburizers may also be used. Usually they are cyanide salts melted and heated to a proper high temperature. The case produced by liquid carburizers is usually thin. Liquid carburizers are also used in the process invented by Dr. P. W. Shimer[10] and employed at the Phillipsburg plant of the Ingersoll-Rand Company. The base of the bath is a mixture of specially selected and prepared sodium and calcium chlorides commercially obtainable in two grades, one with a melting point of 950 and the other 1150 deg. fahr. A bath is given case-hardening properties by the immersion in it of small lumps of special calcium cyanamide. It is claimed that good results are obtained by this method and that the bath does not give off any harmful gases.

Since even in the case of solid carburizers it is the gases evolved that produce the real carbonization, the gases themselves may be used—for example, carbon monoxide, or such volatile hydrocarbons as benzene, ligroin, etc. The only reason why gases are not used more extensively is because thus far no furnace seems to have been developed that would permit direct gas carburization on a large scale.

Quite often it is worth while to use in case-hardened articles nickel or low-chromium steel instead of plain carbon steel.

When it is desired to case-harden only certain parts of the surface and leave others in their original condition, the parts to be protected from case-hardening may be plated with copper,[13] which gives excellent results provided the copper plating is perfect. A thickness of 0.002 mm. is sufficient if deposited at a current density not greater than 0.2 ampere per sq. dm.

Irregular carburization of iron and iron alloys is due primarily to the employment of the incorrect chemical reactions, and this can be controlled by using steel of proper or improper physical structure and by the mechanical arrangement of steel articles and carburizers. To produce good carburizing it is necessary to conform to the following requirements:[18]

Uniform grain structure of steel or iron, produced by heat treatment prior to carburizing; clean surfaces, free from scale, grease, and matter chemically active below or at carburizing temperatures, which chemical reactivity results in deleterious dilution of the CO gas; arrangement of articles so as to expose all parts of the surface uniformly to the carburizing gas (CO); a container so sealed that a positive pressure is maintained therein during the period of carburizing; a uniform temperature above the upper critical temperature which changes the iron to the gamma condition and produces a solid solution of carbide in gamma iron (austenite); for partial or selective cementation, the use of solid-copper protecting equipment in preference to any of the present methods, including copper plating.[19]

Case-Hardening by Boron and Nitrogen. Boron[11] penetrates iron much as does carbon. Boron-hardened steels differ markedly in their response to heat treatment and are never so hard as steels containing an equivalent of carbon. Nitrogen is much more readily absorbed by a boron steel than by a carbon steel, possibly because boron nitride forms at temperatures above those at which iron and nitrogen unite to form a stable nitride. Nitrified boron steels exhibit extreme brittleness and a marked tendency toward exfoliation and chipping.

Special steels may be hardened by heating them at 580 deg. cent. (1076 deg. fahr.) in an atmosphere of nitrogen[12] which slowly diffuses into the outer layers of the metal-forming nitrides.

Case-Hardening by Nitrogen

This process has lately gained considerable acceptance for certain purposes and is now operated, among others, in the United States. Briefly the process consists of subjecting the parts to be hardened to the action of ammonia gas at a temperature of approximately 500 deg. cent. for a period of time varying from 40 to 120 hr.[22]

The ammonia is dissociated and a portion of the nitrogen thus

formed passes into solid solution in the outer layers of the parts.

The steels used for this process are of a special character. Ordinary structural steels such as the nickel and nickel-chrome steels undergo little increase in hardness by this treatment. Dr. Fry found that in steels containing aluminum and silicon, the surface layers reached a hardness of approximately 900 Brinell. The steels being used for this purpose, which is finding extensive application on the Continent, contain 1.5 per cent of chromium and 1.5 per cent of aluminum with a silicon content slightly higher than that usually met in with structural steels. A recent alteration in the composition consists in the addition of 1.5 to 2 per cent of nickel also. This is said to improve the physical properties of the core and also to lessen the tendency of the case to chip or crack when subjected to shock, without materially lessening the hardness.

The carbon contents of the steels are varied from 0.20 to 0.40 according to the physical properties desired in the core of the finished parts. The steels present no difficulty in forging and machining, and the physical properties (after suitable heat treatment) are very similar to those of ordinary nickel-chrome steels. The steels are heat treated in the forged, rolled, and rough-machined condition to give the required physical properties. The most used steel is one which gives 50 to 60 tons tensile after heat treatment, which is easily machined in this condition. The heat treatment consists of water or oil quenching at a temperature of 850 to 900 deg. cent., followed by a tempering in the region of 600 to 670 deg. cent.

One of the most notable and valuable features of the process is the small amount of distortion which the parts undergo during the nitrogen treatment. This is, of course, due to the low temperature of the process and the fact that no further treatment is required after the parts have been cooled down after being subjected to the gas.

The furnaces in which the treatment takes place are electrically heated. This is on account of the close temperature control necessary and the fact that for this type of process, due to the low temperature and the long duration of the heat, electricity is easily the cheapest heating medium.

For a "case" of 0.020 to 0.025 in., approximately 50 hr. at temperature is needed, and for 0.032 to 0.036 in., 100 hr. This long period constitutes one of the disadvantages of the process. After the heat is finished the current is switched off and the furnace allowed to cool down naturally, the gas being circulated until the temperature has fallen to about 200 deg. cent.

The pieces after removal from the box present a matt appearance, with here and there variegated violet markings. They have a soft skin approximately half a thousandth thick, and underneath this the hard nitrogenized layer. This soft skin is removed either by sand blasting or polishing.

The nitrogenized layer is intensely hard and quite incapable of being marked with any sort of file. Scleroscope readings usually

give figures in the region of 107–112, and the diamond indentation tests gives a Brinell hardness of about 900.

As would naturally be expected from the hardness figures, the "case" is more brittle than ordinary case-hardened work, and for this reason sharp corners should be avoided on nitrogenized work. Although the total depth of case in nitrogenized work is in the order of 0.025 to 0.038 in., according to the length of time of the heat, the intensely hard portion, that is, that portion 850 to 900 Brinell, is only five- or six-thousandths of an inch deep.

Laboratory and service wear tests have proved that the wearing properties of the nitrogenized layer are in accordance with what one would expect from the Brinell hardness. In fact, in many cases they have proved even better. Wear tests on an Amsler abrasion testing machine have shown the rate of wear to be approximately one twenty-fifth of that which occurred with a nickel-chrome steel case-hardened by ordinary methods. A paper read at the recent convention of the American Society for Steel Treating in Detroit on the wear of plug gages gave similar figures for nitrogen-hardened steel. Gages hardened by this process gave an infinitely longer life than similar gages from ordinary case-hardened steels under all conditions of abrasion. It is interesting to note here, though, that under certain abrasive conditions chromium-plated gages gave a longer life than nitrogen-hardened gages, while manganese steel gave very poor results for this particular duty.

It is possible that due to the extreme hardness of the case, trouble may be caused through severe shocks, especially on the edges of the work. It is not certain how such parts would behave under conditions of loading involving very heavy surface pressures. It should be remembered that case-hardening steels with core strengths of 90 to 95 tons are being fairly regularly used in the automobile industry now, and superimposed upon this is a carburized case of anything up to 0.050 in. deep.

Whether nitrogen-hardened parts with a maximum machinable core strength of 60 to 65 tons and a case of 0.030 to 0.038 in. will stand up without indentation under such conditions, remains yet to be proved. The advantages of the process are the excellent hardness and wearing properties of the case, and the very slight distortion even on the most intricate parts. There are many parts which have been treated by this process successfully where ordinary case-hardening methods were totally inapplicable, due to the delicacy and intricacy of the parts and the tremendous distortion which took place when such methods were tried.

Another feature of this process which warrants attention is that the hardened case retains its full hardness up to a temperature of 500 deg. cent. Altogether the process appears to be one with considerable possibilities, and deserves the attention of all engineers interested in case-hardened work. It should be mentioned that the process is fully protected in all countries.

Nomenclature of Heat Treatment

The following definitions have been proposed by the American Society for Steel Treating:

Annealing. Heating above the critical temperature, followed by a relatively slow rate of cooling.

Loneal. Heating below the critical temperature, followed by any rate of annealing.

Normalizing. Heating above the critical temperature, followed by an intermediate rate of cooling. (Note: In good practice, the heating is considerably above the critical temperature.)

Spheroidizing. A long-time heating at or about the critical temperature, followed by slow cooling throughout the upper part of the cooling range. (Note: For the purpose of spheroidizing the cementite in high-carbon steels.)

Hardening. Heating above the critical temperature, followed by a relatively rapid rate of cooling.

Tempering. Reheating, after hardening, to some temperature below the critical temperature, followed by any rate of cooling.

Carburizing. Adding carbon, with or without other hardening elements such as nitrogen, to wrought iron or steel by heating the metal below its melting point in contact with carbonaceous material.

Case-Hardening. Carburizing the surface portion of an object and subsequently hardening by suitable heat treatment.

Cyaniding. A specific application of carburizing where the object, or a portion of it, is heated and brought into contact with cyanide salt.[23]

A somewhat different set of definitions was submitted recently to the members of the Iron and Steel Division of the Society of Automotive Engineers. These were published in *Machinery*, New York, vol. 30, June, 1924, p. 757.

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CHAPTER V

CAST IRONS

The term "cast iron" has two widely different meanings. When an engineer specifies that the foundation in a machine will consist of two cast-iron bars he clearly means gray cast iron, which is by far the most widely used type of cast iron in commerce and engineering; but when a metallurgist speaks of cast iron he means the whole series of metals beginning with the softest gray iron and going through to the hard white iron, and including such widely different materials as plain gray iron, chilled iron, malleable iron, pearlitic iron, and the whole family of heat-treated and alloyed irons. It is because of this that the plural, "Cast Irons," is employed in the title of this chapter. Moreover, the conception of cast iron in all its forms is rapidly undergoing an important modification. Up to a few years ago probably the only two types of cast iron known were the metal as it came from the mold, which included gray iron, mottled iron, and chilled iron, all of which were brittle, and malleable iron, which was practically the only commercially used type of heat-treated cast iron and which had a certain amount of malleability, a tensile strength from 50 to 60 per cent superior to ordinary gray iron, and a certain amount of elongation. Also, only cast irons free from special alloying elements were commercially known.

Within the last ten or twelve years, because of a better understanding of the metallurgical principles underlying the production of iron-carbon alloys, a whole new series of cast irons have been created, some of them possessing higher ductility and tensile strength than the old, untreated, cast irons, and some endowed with properties which no alloy of equal carbon content ever possessed before. There has also been a tremendous improvement in the methods of manufacture of malleable iron which has resulted in the production of what may be considered to be a new material. Because of this, the subject of cast irons acquires a very great interest for the mechanical engineer, as within recent years this family of iron alloys has placed at his disposal many new and useful products, at times fully capable of replacing the more expensive steel castings or forgings.

The following incident may be of interest in showing how things have changed in this respect in American industry. When Mr. John N. Willys some twenty years ago took over what was then the American Motors Co., and has since developed into the Willys-Overland Co., the company had a large number of orders for automobiles on hand, but could not get them out because of the great delays in deliveries of malleable-iron castings and excessive rejections of the material when it was delivered. The situation finally reached such a state that manganese-bronze castings costing

many times more per pound than malleable castings were substituted, and it was only then that a steady flow of automobiles began from the factory. Today hundreds of thousands of pounds of malleable castings are delivered of uniform quality and of strength far superior to the best that was available twenty years ago.

Looking over the whole series of alloys of carbon and iron beginning with the softest iron and ending with the cast-iron group, it would appear that as the carbon content increases from zero to 0.89 per cent there is a gradual replacement of the original ferrite by pearlite, till at the eutectic limit the pearlite forms the whole mass of the metal. With the further increase of carbon some of this pearlite is replaced by free cementite till at 1.70 per cent of carbon (point *E*, Fig. 16, p. 24) the mass consists of pearlite (86 per cent by weight) and free cementite in the ratio of 6.1 of pearlite to one of free cementite.

As we pass beyond the 1.70 per cent carbon we run into the possibility of formation of two groups, which may be either gray irons or white irons. The increase of the carbon content[32] from 1.70 to 4.30 per cent is accompanied by a continuous replacement of the structure which existed at that time (Howe calls it "1.70 per cent austenoid," in view of the fact that it is a product of the transformation in cooling of the austenite of 1.70 per cent carbon which forms in the solidification of all alloys containing more than 1.70 per cent of carbon) by a eutectic, till at 4.30 per cent of carbon the eutectic forms the whole mass. With further increase of carbon content this eutectic is in turn replaced by cementite, till at 6.67 per cent of carbon the mass would theoretically consist of cementite alone, but for certain reasons never does.

There have been a good many attempts to define cast irons in a manner to separate them entirely from high-carbon steels into which they can easily pass. However, most of the definitions given hitherto are not suitable for the state of things that exists today. H. M. Howe[1] states, "Cast iron usually contains so much carbon that it is not usefully malleable at any temperature." But the late Professor Howe's former associate, Prof. Bradley Stoughton,[2] describes a cast iron which can be "tied into knots." Better definitions can probably be obtained by going back to the constitutional diagram of the iron-carbon system (Fig. 16, p. 24). It was pointed out there that as we move from left to right we pass gradually from hypoeutectoid steels consisting of ferrite and pearlite through the stage of purely pearlitic (eutectoid) steels into hypereutectoid steels consisting at room temperature of cementite and pearlite, the amount of cementite increasing with the carbon content. This constitutes the region lying to the left of *E*. To the right of *E* begins another region which may be classified as that of cast irons. The slowly cooled alloys of concentration lying between the points *E* and *B* should consist at temperatures below *PK* of crystals of cementite imbedded in pearlite, provided the cooling

took place at a certain moderate rate. If this did not happen, then the structure would be one containing pearlite and products of the degeneration of cementite, with or without the presence of undegenerated cementite.

From this point of view the diagram of Fig. 26 is of great interest.[3] In this diagram the abscissas represent carbon content in per cent and the ordinates, temperatures in degrees centigrade. The conditions of equilibrium are then represented by various lines and fields on the diagram. Thus above *ABD* the metal is a homoge-

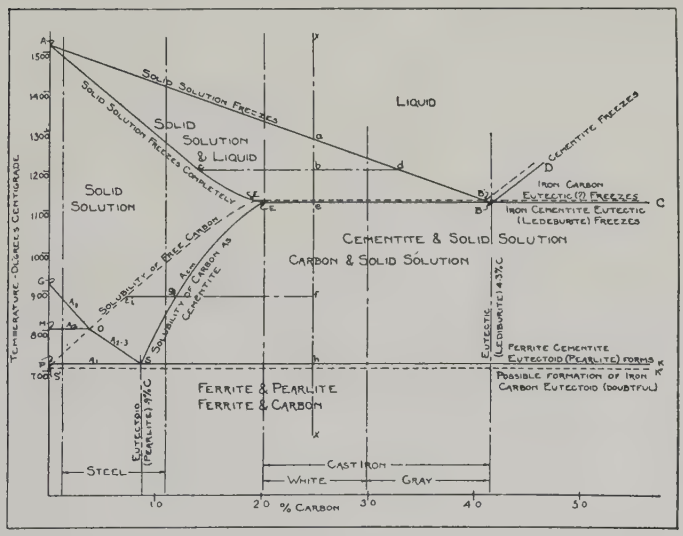

Fig. 26 Benedicks' Diagram Recording the Equilibrium Conditions in Terms of Temperatures and Agraphitic (non-graphitic) Carbon
(From American Malleable Cast Iron, H. A. Schwartz, Penton Pub. Co., 1922, p. 47. Reproduced by courtesy of the publishers.)

neous liquid. *ABD* shows how the carbon content affects the beginning of freezing, while *AEBC* does the same for the completion of freezing. In the areas *AEB* and *DBC* the metal consists of a mixture of a homogeneous liquid and (theoretically) a homogeneous solid, which, as has been shown elsewhere, is a "solid solution." The alloy of lowest freezing point *B*, carbon 4.3 per cent, is known as the eutectic. The solidification of non-eutectiferous alloys to the left of *E* is completed by the freezing of a solid solution of composition dependent on the original carbon content at temperatures marked by the line *AE*. Below the freezing point other rearrangements occur in the solid metal.

Another diagram for cast iron (Fig. 27) has been plotted by Dr. Eduard Maurer.[33] (Cp. also Piedboeuf's diagram on p. 138.) In plotting this diagram, he follows the system for such diagrams

introduced by Guillet (compare Fig. 34) and uses silicon contents for abscissas and carbon contents for ordinates. In cast irons only the following constituents can be encountered: Carbide of iron with pearlite (ledeburite) in white cast iron, graphite with ferrite and pearlite in ferritic gray cast iron, and graphite with pearlite without ferrite in pearlitic gray cast iron. The presence or absence of these constituents depends on one hand on the carbon content and on the other hand, on the silicon content. Dr. Maurer selected as a starting point for his diagram the eutectic containing 4.3 per cent carbon and named this point A. The point B on the silicon axis he located at 2 per cent silicon, having found in a previous investigation that steels containing 2 per cent silicon can be cast with contents up to 1 per cent carbon without any separation of the

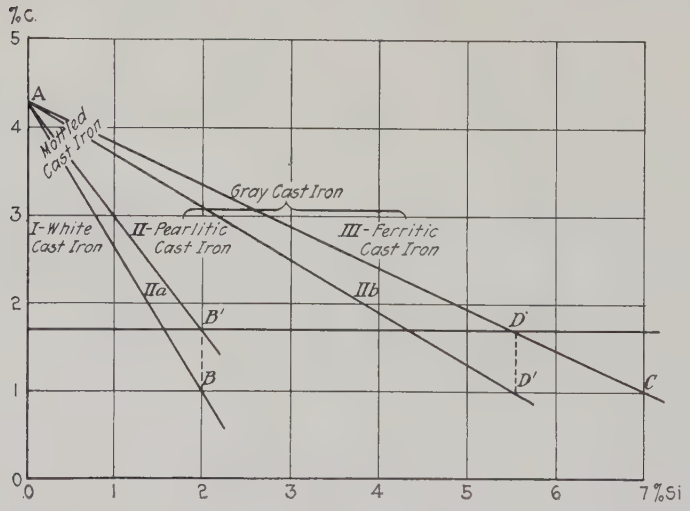

FIG. 27 THE MAURER CARBON-SILICON DIAGRAM OF CAST IRONS

graphite. Point C corresponding to a 7 per cent silicon content was taken from the Guillet diagram for silicon steels. By connecting the points B and C with A he obtained three fields of which field I represents the region of white cast iron, field II the pearlitic, and field III the ferritic irons. The transition fields IIa and IIb between the corresponding three fields have been determined by projecting point B upward on to the horizontal axis which passes through the point 1.7 per cent carbon, this carbon content representing the border line between steel and cast iron. On the other band, point D, which is the intersection between the 1.7 carbon line and the AC line, is projected downward on to the axis of abscissas. In this way B' and D' are obtained, and when connected with A establish the intermediary fields.

Dr. Maurer has investigated personally a number of samples and compared the indications of his diagram with data of samples investigated by others, and found that the diagram represented the situation correctly.

The mechanism of formation of cast irons is not entirely certain as yet. It would appear, however, that the molten mass represents a mixture, probably a solution of carbide of iron in iron. The line *BC* of Fig. 16 represents probably the temperatures at which the carbide and molten iron are in equilibrium. A further cooling results in the precipitation of free carbide and it is only after the resolution of the eutectic at about 1130 deg. cent. or line *ED*,

FIG. 28 EUTECTIC CAST IRON RAPIDLY QUENCHED IN WATER SHOWING LEDEBURITE (WÜST)

(From Cast Iron in the Light of Recent Research, by W. H. Hatfield, Charles Griffin and Co., London, 1918.)

into free carbide and austenite that the free carbon is formed. The degree of rapidity with which the cooling of the iron both before and after freezing takes place is the factor which mainly determines the ratio of free to combined carbon in the finished product, assuming the same chemical composition. Wüst[4] investigated the composition of the eutectic point and its temperature of solidification as well as the microstructure of this eutectic alloy. Fig. 28 shows a sample of cast iron of eutectic composition quenched in water and magnified 100 times. The structure presented by the solidified eutectic is clearly distinct from any of the steel structures such as shown, for example, on pages 14 to 17, and Wüst proposed

to call it "ledeburite." From these tests it would appear that the production of the graphite takes place progressively during the recalescence observed at about 1130 deg. cent. (line *ED* or *BD*).

Various Kinds of Cast Irons

Cast iron, using the term in the broad sense, is so affected by its composition, process of chilling, and, at times, subsequent heat treatment that a variety of materials is obtained possessing a wide divergence of properties. Cast iron may be made soft enough to be perfectly machinable and also glass-hard; very brittle, and so tough that it can be tied in knots, and may have a range of tensile strength from about 18,000 lb. to 55,000 lb. per sq. in. The following is an enumeration rather than a classification of the types of cast iron of special interest to mechanical engineers. It does not claim to be logical but it is believed that it will be of practical interest.

Direct Castings. In a broad sense the product of the blast furnace is cast iron. It is not usually so called, because in the vast majority of cases it is poured into pigs or, after passing through the mixer, is delivered to bessemer converters or open-hearth furnaces. Many efforts have been made, however, to produce castings directly from the material delivered by the blast furnace.

The Ford Motor Co. tried at first to make castings with the metal directly as obtained from the blast furnace. This did not prove successful. The company has therefore installed large (15-ton) Heroult electric furnaces. No melting is done in these furnaces, but a mixture of 40 per cent of blast furnace metal and 60 per cent cupola metal is poured into the electric furnace and raised to the proper temperature. Castings of cylinder blocks are said to be made in a very satisfactory manner.

Gray Iron. The characteristic feature of gray-iron castings is that more or less of their carbon is present as graphite, while in white iron, as will be seen later, it is present as cementite, and in malleable iron as "temper" carbon. (The meaning of this latter term will be explained in connection with the production of malleable castings.) This graphitization is usually far from complete, though in some exceptional cases, as in "black heart" malleable castings, it may be practically complete. When a mechanical engineer speaks of "cast iron" without specifying it further, he usually means gray iron, and the author has received a letter from Dr. Richard Moldenke, Chairman of the Committee on Cast Iron of the American Society for Testing Materials, stating that whenever cast iron is referred to in the specifications of that society without further explanation, gray cast iron is meant thereby. Gray cast iron is soft and easily machinable, except for the outside skin of the castings, which may have sand from the mold burned into it and therefore be very hard on the tool, producing a kind of abrasive action. As appears from Fig. 29, the carbon is in

the form of flakes. The presence of these flakes does not directly affect the strength of the iron matrix, but acts as that much hollow space, reducing the amount of the material over the cross-section capable of resisting mechanical stresses. Because of this gray cast iron has a comparatively low tensile strength, varying usually from 18,000 lb. and less per sq. in. up to 22,000 or 23,000 lb. Furthermore, the shape of the cavities in the iron matrix produced by the carbon flakes, as appears from the same illustration, is extremely irregular, abounding in sharply bounded promontories. Each one of these acts in essentially the same manner as a notch in the notch impact test, and reduces at numerous points distributed throughout the material the ability of the latter to withstand shock, making gray cast iron brittle.

White Cast Iron. Carbon in cast irons may occur essentially in one of three forms: as free carbon, in one of two main forms, viz., as graphite flakes or plates (in gray cast iron), or as rounded globules, as in malleable iron—described more fully below. It may also occur combined with iron, i.e., as cementite. This happens in white cast iron (Fig. 33), to which cementite imparts its properties of hardness and brittleness. Because of the combination of these properties, white cast iron has few industrial uses.

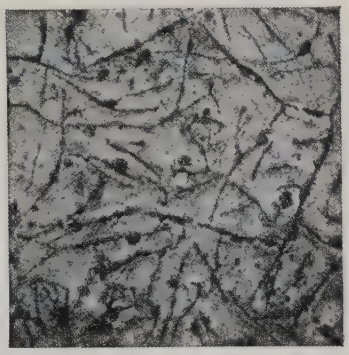

FIG. 29 MICROSTRUCTURE OF GRAY CAST IRON AS CAST

(Black lines represent graphite plates.) (From Cast Iron in the Light of Recent Research, by W. H. Hatfield, Charles Griffin and Co., London, 1918.)

Mottled Cast Iron is an iron which, because of the conditions of cooling, is an intermediary product between white and gray cast iron, and approaches the properties of either one of the two depending upon which of the two types is prevalent in its structure. The alternation of white and gray spots gives it the mottled appearance which led to the adoption of its name.

Chilled Iron. When pig iron cools from the molten state it holds in solution, probably in the form of carbide of iron, all the carbon which it contains at a given temperature. On cooling, some of this carbon separates out in the form of graphite flakes which are distributed throughout the mass. The remainder stays in the form of combined carbon (cementite), the effect of which is to increase the hardness of the metal. The separation of the graphite, as shown elsewhere in this article, depends mainly upon the rate of cooling, though also upon the silicon content of the metal, so that, all other things being equal, if the iron is cooled very suddenly

and is of proper composition, all carbon may be retained in solution as combined carbon, which renders the iron dense, white, intensely hard, and capable of receiving a very high polish. Such an iron is called "chilled iron." It is used for making railroad wheels, rolls for shaping steel, etc. In making rolls only the exterior layer is given a chill, both because it would be extremely difficult to chill the whole casting quickly enough to produce the required structure throughout, and also because there is an advantage in having the roll possess an extremely hard surface (to reduce the wear against the metal rolled) and at the same time a soft interior to cushion the shocks and thus reduce the breakage of the rolls. This chilling of only a part of the roll is effected by making that part of the mold corresponding to the necks and wobblers of sand, while that part destined to form the body is made up of a heavy cast-iron ring. The rapid cooling caused by the absorption of the heat by the cold ring casting in contact with the molten metal causes a chill on the outer surface of the roll, the depth and hardness of which is controlled by varying the composition of the molten metal.

The following analysis of different parts of a chilled roll is given in The Making, Shaping, and Treating of Steel, by J. M. Camp and C. B. Francis, 2d edition, p. 326:

	Total carbon	Combined carbon	Graphite carbon	Silicon	Sulphur	Phosphorus	Manganese
Chill	3.00	3.00	...	0.90	0.04	0.200	0.25
Mottled	3.00	2.25	0.75	0.90	0.04	0.200	0.25
Gray	3.00	1.00	2.00	0.90	0.04	0.200	0.25

Gun Iron. A certain type of cast iron is referred to at times as "gun iron." Cast iron may be produced in several ways—for example, direct iron from the blast furnace, or it may be remelted in an air furnace, in a cupola, or in an electric furnace. The iron melted in the air furnace is lower in sulphur and in total carbon. Because of this it is generally better and has a more uniform structure, with the grain rather fine even in large sections. Consequently in the early days it used to be employed specially for casting guns. The name "gun iron" is therefore preserved for air-furnace iron, notwithstanding the fact that guns are no longer made of cast iron.

*DeLavaud Metal.** Centrifugally cast pipe has become an important product both in this country and abroad. It is made by several processes, one of which is the DeLavaud process. In this a rapidly rotating, steel, water-cooled mold is used, the metal being delivered from the end of a horizontal spout. The spout is stationary while the mold has not only a rotary movement but moves at

* This term has been borrowed from the Specifications for the DeLavaud Centrifugally Cast Cast Iron Pipe issued by the U. S. Cast Iron Pipe and Foundry Co., Burlington, N. J., the largest makers of this material in the United States.

a certain predetermined speed away from the spout, so that the stream of metal coming from the spout impinges upon the mold and forms something like a ribbon longitudinally wound with overlapping edges. The metal as cast is hard and somewhat brittle. It is, however, passed through an annealing furnace where it is heated for a few minutes to a temperature of the order of 1750 deg. fahr. (955 deg. cent.).

The following information as to the structural condition of the annealed DeLavaud pipe is taken from A Study of DeLavaud Centrifugally Cast Cast Iron, by Arthur Phillips, copyright 1923, U. S. Cast Iron Pipe and Foundry Co., pp. 11–12. According to Mr. Phillips, DeLavaud pipe is made up of three gradually merging layers, namely, an outside layer similar to the structure of malleable cast iron, an inner layer consisting of a steel matrix (containing impurities, of course), the continuity of which is taken up to some extent by graphite, and an innermost layer of gray cast iron. The high tensile strength of the DeLavaud pipe, which tests have shown to be of the order of 32,000 lb. per sq. in. average with an elongation of 0.5 per cent in 2 in., is probably due to this unusual combination and arrangement of structural elements, as the chief weakening and embrittling element in gray cast iron is the soft and friable graphite, and in the DeLavaud pipe the center of the wall consists of a steel matrix containing graphite in small areas which do not break up the continuity of the mass as much as the usual irregularly shaped flakes.

The Wasson Piston Ring Co.[5] attempted to use the DeLavaud method for casting piston rings. The castings came absolutely hard and were annealed in the same way as is done with pipe. The annealing process, however, precipitated the carbon out of the combined state into temper carbon and not graphitic carbon. The result was that when the rings were put into a test aircraft engine, the latter started off with the highest efficiency that it had ever shown, but the efficiency very soon fell off and at the end of 54 hours the rings had lost twenty thousandths of an inch on the wall and the cylinders were cut all to pieces. As the carbon was in the form of temper carbon, the material was not suitable as a bearing material.

Case-Hardened Gray Cast Iron. At first glance, case-hardening of gray cast iron does not seem to be a profitable operation. A gray cast iron obviously contains more carbon than can be retained in the combined condition, and it would not seem that heating it in a carburizing material could increase the carbon content of this surface. And yet from tests made, for example, by H. B. Knowlton, and from commercial practice it would appear that case-hardening does produce very interesting results. In the tests referred to bars were packed in pipes with an ordinary carburizing material such as is commonly used in case-hardening steel. Samples were then tested by placing them in a vise and striking them with a 3-lb.

hand hammer. While samples that were not carburized were easily broken by a single blow, the carburized samples could not be broken by the 3-lb. hammer at all, and were broken only with a 10-lb. sledge. In the fractures there was a difference between the center and the outer layer somewhat similar to the difference between the case and the core of a case-hardened steel specimen, though not as pronounced as in the case of steel. Microscopic investigation showed a broad zone at the edge which was largely pearlite, with indications that the combined carbon in these zones was at least a little higher than in the original casting. While it is not clear just what takes place during the carburizing heat, a great improvement in the mechanical properties of gray cast iron can apparently be produced by this method. However, not enough work has been done to show what composition of cast iron would be the more suitable for case-hardening.

Annealed Gray Cast Iron. Among the processes for annealing gray cast iron attention has been drawn to that of Alexander K. Schaap described by Prof. Bradley Stoughton.[6] In this process the casting is heated to a temperature slightly above the critical (1600 deg. fahr. = 871 deg. cent.), while protected in a muffle surrounded by a gas flame and open at the top. A good deal depends on the construction and material of the muffle for the success of the process, and, for example, a crack developed in the side of the muffle produces hard spots opposite the opening. When the iron reaches the proper temperature the muffle and its contents are removed from the furnace and allowed to cool in the open air, the casting being protected from drafts by laying a cover on top of the muffle. In this way it requires about fifteen minutes for the iron to cool to a black heat, after which it may be cooled in the open air.

The material is said to have very unusual qualities, particularly as regards resiliency. A thin bar may be coiled up into a spiral and used as a spring, although, of course, it will not be nearly as strong and resilient as a tempered-steel spring. This iron does not "grow" by repeated heatings and coolings and does not revert to the white cast iron formed upon heating followed by rapid cooling.

The original structure of this metal as cast consists of coarse grains of graphite leaving only short and separated metallic paths of rupture. The treatment produces an almost continuous metallic phase with relatively small particles of carbon between. It would appear that in the course of treatment the following takes place: At a temperature of 1600 deg. fahr. or slightly above the coarse flakes of graphite are apparently absorbed to some extent in the solid solution existing at that temperature. With the moderately slow cooling which follows, the solid solution breaks up into ferrite and pearlite mixed with fine particles of carbon surrounded by crystals of ferrite from which it has separated. The pearlite matrix seems to be semi-globular in structure rather than the

lamellar (plate-like) pearlite of annealed white cast iron. (Fig. 30.)

The structure of the iron indicates clearly the difference between this metal and malleable cast iron made by the usual annealing process of $6^1/_2$ days: The latter consists of a ferrite matrix with particles of temper carbon; the purpose of the annealing is to

FIG. 30 ANNEALED CAST IRON
(From an article by Prof. Bradley Stoughton in *The Iron Age*, Jan. 3, 1924, by courtesy of the author.)

completely decompose the cementite of pearlite into carbon and ferrite. This doubtless explains the necessity for the long time of annealing for malleable cast iron, and also the lack of resiliency, which could not be expected in an almost continuous ferrite phase. On the other hand, the resiliency of this annealed iron, which so

resembles that of steel, is apparently due to the pearlitic, instead of ferritic, phase.

Statements have been made that the same results can be achieved without resorting to the particular process (use of muffle) employed by Mr. Schaap.

Pearlitic Cast Iron.[7] This is one of the latest important developments in cast irons, but the information available about it is still somewhat sketchy. Pearlitic cast iron is an iron which is of such a composition that if cast in an ordinary mold it would give a white fracture. Through being cast, however, in a mold heated to a certain temperature either before or after casting and through having, therefore, the cooling of the metal retarded in a certain manner, a microstructure is produced which consists of a pearlite matrix with enclosures of free graphite and which therefore gives a metal of superior strength. The interesting part about pearlitic cast iron is that it represents a deliberate and successful attempt to create in a metal a structure which previous metallographical investigation has shown would contribute to the improvement of its physical qualities.

Pearlitic cast iron is an iron which has a low silicon and low total carbon content, the temperature of the mold depending on these two factors of composition and the thickness of section. Thus, for example, with a total carbon content of 3 per cent, including graphite 2.15 and silicon 1 per cent, the mold should be reheated to a temperature varying as follows with the thickness of the section of the casting: Thickness of section 0.4 in.—to about 200 deg. cent. (392 deg. fahr.); thickness of section about 0.8 in.—to about 150 deg. cent. (302 deg. fahr.); and thickness of section 1.2 in.—to about 100 deg. cent. (212 deg. fahr.). While the plans controlling this process (it was invented by Diefenthaler at the Lanz Foundry in Germany) specify the manganese and phosphorus contents, it does not appear that they attach any importance to them. The sulphur content does not appear to be of importance unless excessive.

Malleable Cast Iron. There are two products coming under this name. The first historically, though the lesser in importance industrially today, is the so-called "white heart" malleable iron invented by Réaumur in the first quarter of the eighteenth century and still made on a restricted scale in Europe. This iron is produced by packing small white-cast-iron castings in pulverized hematite ore or mill scale and heating them to bright redness for many days. The surface becomes decarburized by the contact relation between the cast iron and the packing. As practiced today, however, the heat treatment is insufficiently deep and the cooling of the piece excessively rapid. Because of this, part of the carbon is in the free state and part in a solid solution. The structure of the material lacks in uniformity and the central part of the casting, especially if it is comparatively thick, retains the normal structure of white iron. If the casting comprises sections of different

thicknesses, some of them will be free of this white-iron core or heart and some will possess it, with the result that the pieces are of unequal strength and somewhat subject to warping and cracking.

The American method, invented toward the end of the first half of the nineteenth century by Seth Boyden in Newark, N. J., is worked in an entirely different way. As in the European process, the start is made with white iron, but this is annealed for a longer or shorter time at a temperature well above the upper critical point and then cooled extremely slowly at a rate not exceeding 10 or 11 deg. fahr. per hour as a maximum. The result is a material of great uniformity of structure, even in complicated shapes, and of a high tensile strength and high coefficient of elongation.

This has been materially assisted by the way manufacturers of malleable-iron castings have gone about their business in the United States, namely, by adopting the so-called "certified castings" scheme. The majority of manufacturers have formed an association which has appointed a laboratory as their testing plant. Sample bars from various heats are sent by each manufacturer to the central laboratory where they are tested, and only those manufacturers whose bars during a certain period have maintained a uniformly high standard are entitled to call their products "certified." When the bars do not live up to the desired standard, engineers are sent out from the central laboratory to investigate the manufacturing conditions at the plant. By this means of inspection and cooperation the average standard has been raised and some of the manufacturers have been enabled to attain a remarkably high state of excellence of their products.

Most of the malleable iron made by the better manufacturers today ranges from 2.30 to 2.70 per cent carbon before annealing.[5] The size of the casting affects the rate of cooling, and thereby the tendency to graphitize on freezing. This tendency can be controlled by varying the silicon content. With little or no silicon, graphitization in the annealing process is retarded to a commercially prohibitive degree. When too much silicon is present, graphitization may take place during freezing, which is undesirable. Because of this the silicon content varies from 0.60 to 0.80 per cent, the general practice being to vary the silicon inversely with the carbon, and for a given carbon inversely with the cross-section of the casting.

As cast, white iron consists essentially of cementite embedded in pearlite or a solid solution of iron. When this is raised to a temperature well above the Ac_1 point, say, 1700 deg. fahr., a decrease in cementite and an increase in the formation of solid solution takes place.

As the heating at 1700 deg. is continued the cementite breaks down and produces free carbon. While, however, the free carbon in gray iron is in the form of irregular flakes, the free carbon pro-

duced from cementite under the conditions here described appears in the form of fine globules distributed through the metal mass with fair regularity. Such carbon is called "temper" carbon. The structure then consists of temper carbon and a solid solution of carbon or carbide of iron in iron (there is still some doubt which is correct), and the product is still whitish in fracture and very brittle. If, now, the temperature is carried down to 1300 deg., (i.e., below the Ar_1 point), or slightly below that, complete graphitization of the product takes place. A good deal depends on the duration of the first heating and subsequent cooling. Commercial practice in America involves a maximum temperature of the casting for a period from 24 to 60 hr. and an average rate of cooling from this not faster than 10 deg. per hour, preferably less, particularly near the critical point.

The essential difference between malleable cast iron and all other kinds of cast irons lies in the fact that in malleable iron the carbon is always in the state of "temper carbon," i.e., distributed throughout the metal in very small globules of considerable regularity. It must, however, be understood that except for the shape in which they occur there is no essential difference in crystal structure between coke, graphite encountered in gray cast iron, charcoal, and temper carbon.[33]

An interesting example of what may be considered as the most modern type of annealing plant will be found in the installation of the International Harvester Co., described in *Foundry*, vol. 52, no. 2, Jan. 15, 1924, pp. 43–50. Among other things accomplished there, the time of anneal was cut by the use of a furnace of the tunnel type. The average tensile strength of the product is given at 52,048 lb. per sq. in. with an elongation of 13.80 per cent in 2 in.

The necessity of holding the iron in the first heating stage and subsequently in the cooling stage for a time varying from 5 to 9 days naturally enormously increases the cost of the product, both on account of the fuel consumption and on account of the low factor of production per unit cost of the plant. There have been numerous attempts to produce malleable iron by means of only a very short anneal.[9] In one case the white iron contained 2.23 total carbon and 0.94 silicon. The material was heated for three hours at 1700 deg. fahr., then for one hour at 1560 deg. fahr., and was cooled uniformly to 1320 deg. fahr. for 14 hours and then to 1200 deg. for 12 hours, and it is believed that an even more rapid treatment is possible. It is claimed that a material was produced with tensile properties varying from those of malleable iron to values of about 70,000 lb. per sq. in. strength and 4 per cent elongation, and that even higher values were obtained. This product is not strictly a malleable iron, though it may take its place. As a matter of fact, attempts to achieve such results are not at all new, and as early as 1902 Alex. E. Outerbridge, Jr., described his work of very much earlier date,[10] in the course of which white iron was con-

verted into a machinable material by a short anneal at a very high temperature. The possibility of this as a means of commercially producing standard-specification malleable-iron castings is, however, vigorously denied by some men in the trade.[11] In general,

> . . . speed is promoted by graphitizing the cementite at the highest possible temperature, but to a certain extent at the expense of quality. Temper carbon differs from graphite only in form. It has been pointed out that these differences of geometric form are due to the temperature of the metal in which the free carbon is formed. Accordingly, the two forms, temper and graphitic, shade over into each other by infinitesimal degrees, and the temper carbon formed at high temperatures may grow so coarse and flaky as to be almost graphitic.[12]

An interesting application of malleable-iron castings is in the manufacture of heat-treated malleables, which may be used, for example, for tools. The heat treatment depends upon the usage which the casting is to undergo. One of these treatments used for the production of hammer heads consists in heating the hammer head to about 925 deg. cent. (1697 deg. fahr.) and dipping it in warm water two or three times, with intervals of about one second between the quenchings. Among other things, twist drills are produced which work such materials as brass, gray iron, malleable iron, steel, and even hard white iron. The latter is particularly interesting, as usually only high-speed steel can handle it.

Synthetic Cast Iron.[13] Synthetic cast iron is nothing but steel scrap, particularly turnings carburized by melting these materials in the presence of carbon which is introduced simultaneously with them in the melting appliance, the electric furnace being particularly suitable for this purpose.

Its somewhat extensive use was brought about by conditions prevailing during the World War. Then enormous amounts of steel turnings and small scrap became available as a result of the manufacture of munitions. Such turnings can be used in the open-hearth furnace only in briquetted form, as otherwise they are extremely difficult to charge and oxidize so rapidly before melting as to produce enormous losses. The production of the turnings at that time proceeded, however, at such an enormous rate as to exceed all possibility of their being briquetted with the facilities then available. In looking around for a use for them the production of synthetic cast iron was resorted to. It is rather unlikely that it will be carried on under normal peace conditions, except where the amount of small steel scrap and turnings is very large, means for producing cast iron in a regular way are lacking, and electric power is available at a cheap rate. Such conditions may, for example, arrive in some of the South American countries, and perhaps in locations like Seattle.[37]

Semi-Steel. Essentially semi-steel is a metal made up of a mixture of cast iron and steel, a mixture which may be produced in several ways. Thus, molten steel may be added to molten cast

iron in the ladle, or steel in the form of scrap may be charged into the cupola. The latter is the standard method. The best way to make semi-steel appears to be to use a hematite low-phosphorus iron, although in Europe very high-phosphorus iron (1.3 to 1.4 per cent phosphorus) has been extensively used. It is very important to have the manganese in the mixture high, and the best semi-steel for general work should contain 0.75 to 1 per cent of manganese. The best steel to be used for this purpose is mild steel, especially when in the form of plate cuttings and clippings from $^1/_2$ to $1^1/_2$ in. in thickness and in moderate-sized pieces. Crop ends of rails and similar material have also been found suitable, but not high-carbon steel. The percentage of steel used has varied from 15 to 40 per cent, the lower figure for light work and the higher proportions for heavier castings. There is still a good deal of uncertainty as to the methods of its manufacture and processes which have failed in one foundry have been found to be very successful in another, without any clear reason why.

During the war large amounts of semi-steel were used for the manufacture of shells, aerial bombs, etc. and in many cases gave excellent results. The average analysis of good semi-steel, for example, in British aerial bombs, is as follows:

Silicon	2.13	Graphitic carbon	2.55
Phosphorus	0.065	Manganese	0.624
Combined carbon	0.520		

The tensile strength of the material is well in excess of 40,000 lb. per sq. in. In general, it has been found that to consistently maintain a sufficiently high standard in semi-steel a foundry should produce substantial quantities daily, and it is very difficult to produce good material on a small scale or by incidental work. It has been found that when semi-steel is annealed at a temperature from 760 deg. to 800 deg. it becomes very soft, with a certain amount of malleability and ductility, but loses from a quarter to one-third of its tensile strength.

Annealing at a lower temperature has been tried with a much smaller loss in tensile strength.[14,15]

Alloying Elements in Cast Irons

It is legitimate to consider all the elements in cast irons except iron and carbon as alloying elements. Some of these, as sulphur and phosphorus, may be also regarded in the light of impurities, as they mainly come from the ores or fuel, and the metallurgist has to keep them down to a limit rather than, except in some cases, deliberately introduce them. Other elements, such as nickel, are introduced deliberately, in order to achieve a certain purpose such as to increase the strength of the material. The information available as to the influence of the alloying elements in cast irons is still somewhat sketchy, particularly with respect to the rare metals.[38]

Silicon. Next to carbon, silicon is the constituent of cast iron capable of exerting the greatest influence on the structure of the material.

In general, it has been found that as the silicon is increased the carbon changes from the combined to the graphitic state. It is important to remember, however, that this influence may be either assisted or counteracted by other factors, the most important of which are the rate of cooling, the size of the casting, and the casting temperature. The size of the casting in itself is important only because, all other things being equal, it determines the rate of cooling, a thin section obviously cooling faster than a thick, heavy one. Because of this, more combined carbon will be found in a thin section than in a thick section (assuming the same silicon content in both). The rate of cooling is important because the faster the cooling, the more will there be tendency toward the formation of combined carbon. The casting temperature is also important. It has been found that the higher the casting temperature, the more tendency there is toward holding the carbon in the combined form. W. H. Hatfield[16] carried out some tests in the course of which he cast two bars 2 in. × 1 in. × 12 in. from the same ladle of iron, the first bar being cast at 180 deg. cent. higher temperature than the other. Upon breaking the bars the higher-temperature one was found to be mottled white, while the low-temperature one was found to be gray. The microstructure in the white areas of the first corresponded with the normal white-iron cementite-pearlite structure, while that cast at the lower temperature upon examination proved to have a microstructure substantially approaching that of regular gray iron.

In this connection Fig. 31 (reproduced from p. 91 of Das Technische Eisen, by Dr. Paul Oberhoffer: Julius Springer, Berlin, 1925) is of interest as it shows the influence of the various constituents of cast iron upon the formation of graphite. In this figure the graphite is expressed in percentages of the total carbon, and it would appear therefrom that silicon up to about 4 per cent increases the formation of graphite. When, however, present in excess of it, it evidently begins to act the opposite way. It would appear also that there is a certain irregularity in its action between 0.3 and 1.1 per cent.

Sulphur. The actual influence of varying proportions of sulphur upon the physical properties of cast iron is not yet clear. It would appear, however, that in the absence of manganese it assists in retaining the carbon as a carbide, thus producing hard iron. If the iron is very high in manganese, manganese sulphide is formed and the hardening action is neutralized, but other effects are produced.

It does not appear that small percentages, say, up to 0.08, affect the mechanical properties of cast iron seriously, and whatever influence it has is largely concealed by such other factors as tem-

perature, cooling, etc. It would also appear that the hardness of the iron is not substantially affected by low sulphur, while its ability to bend and its tensile strength increase with sulphur up to 0.1 per cent. When, however, sulphur content is high, hard spots

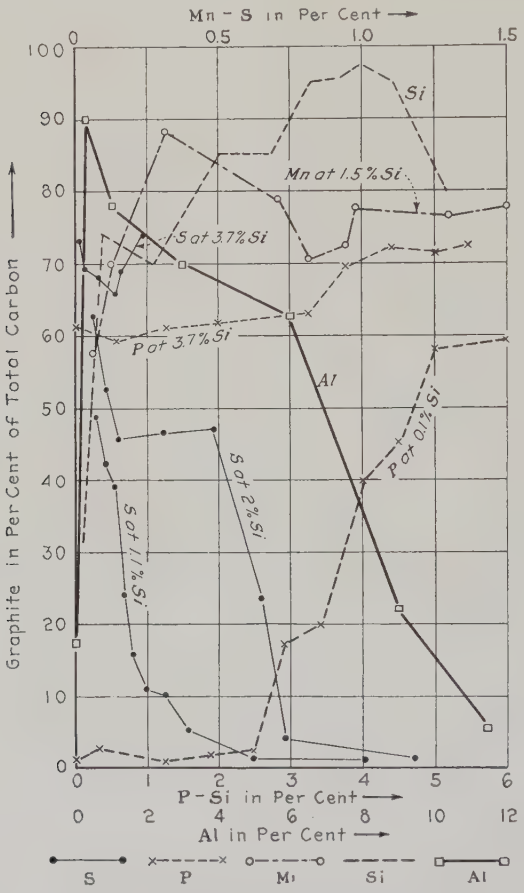

Fig. 31 Influence of Some of the Elements Present in Cast Iron on the Formation of Graphite

(Based chiefly on results obtained by Wüst and his collaborators.)

develop and the iron becomes brittle. High percentages of sulphur are often encountered in iron which has been much remelted or in iron in which a large percentage of scrap, possibly remelted before, is employed. Lately a process has been developed for lowering the sulphur content in cast iron by a certain use of soda ash.[39]

Manganese. While it is known that manganese has an important

effect on the properties of cast iron, its actual influence is still not quite understood. If manganese and sulphur are both present, a compound manganese sulphide is formed which does not affect the properties of the carbon. In steel the presence of manganese is often undesirable. In rolled products it is apt to roll out into a thread or streak in the direction of the rolling, which does not materially affect the strength of the metal in that direction but seriously reduces it in the direction transverse to rolling. In malleable cast iron a similar effect is possible. In itself, manganese raises the degree of solubility of carbon in iron.

Phosphorus. The influence of phosphorus has been investigated by Dr. A. E. Stead,[17] from whose observations it would appear that iron and phosphorus alone form mainly a solid solution of phosphide of iron Fe_3P in iron, reaching eutectic composition at 61 per cent of phosphide of iron, and 39 per cent of the saturated solution of phosphide of iron in iron. The effect of carbon is to throw out free phosphide in increasing proportions with each increment of carbon. Apparently there is a competition between carbide of iron and phosphide of iron for iron with which to form a solid solution and carbide of iron prevails. When the carbon has passed the two per cent limit there appears to be evidence of a carbide-phosphide eutectic containing about 6.7 per cent of phosphorus and 2 per cent of carbon. Since both the phosphorus and carbon need a certain quota of iron to be held in solution, it would appear that the presence of either will decrease the amount of the other which can be present in iron. Indeed, Stead found that 1.56 per cent of phosphorus appears to be responsible for lowering the carbon content from 4.10 to 3.75 per cent.

Phosphorus also appears to have an influence on the condition of the carbon in that it increases the ratio of graphite to combined carbon. This has not yet been completely proved, however.

As regards physical properties, it would appear that phosphorus when present in quantities of from 0.3 to 0.6 per cent increases the tensile and bending strength of the iron, but reduces the tensile strength when present in greater quantities. On the other hand, hardness increases steadily with phosphorus content.

A foundryman, especially when making intricate castings, likes to have the phosphorus in his iron high, because of the low melting point of such iron, which reduces the fuel consumption in melting and permits pouring the metal at a lower temperature. The iron, however, is less strong and more brittle, the latter being due to the fact that free phosphide of iron is present and not only does not add anything to the strength of the metal (in this respect it is similar to the flakes of graphite), but is likely to create planes of weakness owing to the differences in the coefficients of expansion between the iron matrix and the phosphide inclusions.

The presence of phosphide of iron is easily detected by the heat-tinting process[18] (p. 58), as carbide of iron on heating takes the

oxidation tints of straw yellow, yellow, brown, red, purple, blue, and silver gray in sequential order. Phosphide of iron passes through the several ranges of color, but not so rapidly as the carbide, so that when the carbide shows under the microscope as red, the phosphide is a pale yellow, and when the carbide has been heated to blue tint, the phosphide will be brown or red-salmon in color.

Nickel. The presence of nickel in cast iron[19,37] causes increased graphitic-carbon formation, i.e., nickel tends, as does silicon, to "gray" the iron. This effect is quite definite but very mild; one per cent of nickel being perhaps equal roughly to from one-quarter to one per cent of silicon in this respect.

The nickel does not form in the carbides, but dissolves in the ferrite of the iron. If the composition is such that combined carbon is present in the castings, this will be fine in structure in the presence of from 1 to 5 per cent nickel, resembling sorbite more than pearlite and being in consequence harder.

Therefore it will be seen that nickel exercises two effects quite opposite in nature; by lowering the combined carbon it softens the iron, but by sorbitizing the pearlite matrix of the iron, it hardens it. Which of these will prevail depends largely on the amount of combined carbon. If this is low in the composition of the iron under consideration, i.e., if the iron is soft and open, the nickel will soften it still further. If it is high, from 0.3 to 0.8 per cent, the hardening effect will predominate, as in fact it generally does in practice.

Grades of gray iron carrying from 0.50 to 0.85 per cent of combined carbon in general will be hardened, strengthened, and toughened by the addition of from 1 to 5 per cent of nickel. Increases of from 15 to 40 per cent in hardness and in bending or compressive strength are thus obtained. The use of nickel is often beneficial, particularly in thin sections, in that good values of hardness may be obtained without incurring the risk of obtaining chilled or mottled iron or hard spots. The hardness obtained in gray iron by nickel additions is not due to an increase in the amount of carbide present as it is when obtained by lowering the silicon content, with consequent attendant machining difficulties, but is due to the superior and finer form of the pearlite or carbide in the presence of nickel.

The effect of the addition of from 1 to 5 per cent of nickel on the fluidity and the shrinkage of cast iron appears to be so slight as to be inappreciable. However, the addition of nickel appears to produce finer-grained castings, particularly in thin sections. The resistance to corrosion of nickel-bearing cast iron is somewhat superior to that of similar iron without nickel, but probably not sufficient to warrant the use of nickel generally to increase corrosion resistance. On the other hand, the resistance to oxidation at high temperatures is increased by the addition of nickel, and some efforts have been made to utilize this feature in a practical manner.

When nickel is used in connection with chromium, the combined

effect of the two elements depends upon their relative amounts, but generally is in the direction of hardening and strengthening the iron and increasing its chilling power.

Nickel cast iron is used for cylinder blocks and pistons of automobile engines by the Cadillac Motor Car Co. among others. From service tests of cylinders this company has found that with the lower hardness a wear of from 0.0015 in. to 0.002 in. was obtained in 20,000 to 25,000 miles and the cylinders would need regrinding. With a Brinell hardness of 175 to 200, however, the cylinders showed a wear of only from 0.00075 in. to 0.001 in. and did not need regrinding. The company credits this increased wear not only to the hardness of the iron, but also to the fine grain and high-luster finish which can be produced with addition of nickel. It has been found that the nickel-cast-iron cylinders at 200 Brinell hardness machine as easily as the nickel-free ones at 150 Brinell hardness.

Mayari Iron. This is an iron made from ores (Cuba) naturally containing nickel and chromium, the former 0.80 to 1.25 and the latter from 1.60 to 2.50 per cent, together with small percentages of titanium and vanadium. The silicon and carbon may be modified within considerable ranges.

It is stated[20] that in this iron the nickel and chromium work to a certain extent in opposite directions, the former tending to separate out the graphite and the latter to hold the carbon in the combined form. It is claimed, however, that Mayari iron gives castings increased strength and solidity. It is used specifically for wear-resisting castings, such as rolls, jaws, and parts for rock crushers, balls, and liner plates for ball mills, rubber-mill rolls, etc. and has been extensively employed in the manufacture of rolls for metal rolling, both chill and sand types.

Chrome-Nickel. Tests made by T. H. Wickenden and J. S. Vanick would indicate that the additions of suitable amounts of nickel-chromium combinations to gray iron increase its strength from 10 to 50 per cent; increase Brinell hardness from 20 to 50 points without impairing machinability; reduce edge, surface, and corner chilling on thin sections or eliminate hard spots; increase toughness and deflection, particularly on thin sections; refine the grain, and produce denser castings. The additions of nickel are from 0.75 to 1 per cent. The amounts of the additions of nickel and chromium vary with the silicon content of the iron, the character of the casting, and the reason for adding the alloy, which means the property which it is desired to improve.

An investigation of the combined effect of chromium and nickel by Piwowarsky showed that certain relative proportions of these elements increased the tensile and transverse strength as well as the hardness and compressive strength without diminishing the resistance to shock and deflection. It was also shown that in the presence of chromium, nickel has nothing like such a powerful

effect in precipitating graphite as when present alone. The experiments of J. W. Donaldson in England with two chrome-nickel irons indicated that adding chromium and nickel in the proportion of two to one allows of the use of a higher percentage of chromium, although the benefits derived from the increased chromium were more than diminished by the accompanying nickel.[38]

Cobalt. O. Bauer and E. Piwowarsky[21] state that cobalt retards graphite precipitation and favors the formation of carbides, its action being therefore exactly the opposite of that of nickel. When present in cast iron it rapidly reduces the ability of the latter to bend, and slowly reduces the tensile and compressive strength of the metal; it slightly increases the hardness.

Titanium.[22,23] Titanium in cast iron acts essentially in the same way with respect to graphitization as silicon, but more powerfully, so that independently of the silicon content the maximum of graphitization is reached at 0.1 per cent of the total titanium content. Until this maximum amount is reached, the influence of titanium in the direction of graphitization surpasses every other influence in so far as the mechanical properties of cast iron are affected. If more titanium is added the graphitization proper is not affected but the mechanical properties of the metal are noticeably improved, and, for example, bending is improved 50 per cent or better.

Uranium.[24] The most important features of uranium as an addition to cast iron are said to be its effectiveness as a scavenger and its influence on the size and distribution of the graphite in the iron. Microphotographic investigation and chemical analysis show that while no change in the composition of the iron occurs because of the addition of uranium, there is a breaking up of the larger graphitic flakes, producing a closer grain and more homogeneous metal. Uranium iron is being used in glass-bottle molds and in the blanks and plungers in bottle machines. Uranium in iron seems also to increase considerably the latter's ability to take chill in casting.

Molybdenum.[25,26] There does not appear to be any reliable information concerning the effect of molybdenum on the combined carbon content. It would appear, however, that its general tendency is to reduce rather than increase the amount of carbide. Experiments carried out in this connection offer no evidence that small quantities of molybdenum affect the combined carbon content of the harder irons. It would appear, however, that on common gray iron molybdenum exerts an all-around improvement, giving the cleanness and fluidity of a soft iron with the properties of a cylinder iron. Molybdenum appears to decrease the chilling effect, although there is an increase in the hardness of the iron itself, and an improvement in the uniformity of hardness and solidity throughout the casting.

Chromium.[25,27] The effect of 0.11 per cent chromium on iron

samples containing 1.30 and 2.0 per cent silicon and total carbon somewhat in excess of 3 per cent has been found to increase slightly the tensile strength, transverse strength, and Brinell hardness. With 0.78 per cent chromium, the tensile strength falls to that of ordinary gray iron and the transverse strength is little affected, but the Brinell hardness is raised 40 points. The value of chromium in cylinder metal is shown to be very limited in the manufacture of small castings. The chill is, however, affected. In ordinary cylinder iron its depth is increased from 0.068 to 0.90 in. by the introduction of 0.78 per cent chromium, a feature of great importance in the manufacture of chilled rolls, car wheels, gearwheels, and castings of any dimensions where toughness and hard wearing surfaces are of importance.

Piwowarsky's experiments show that when chromium is added up to 0.5 per cent the strength and shock-resisting properties of cast iron are increased to the extent of about 10 per cent, while the hardness increases from 20 to 25 per cent. Still more recent experiments of Hamasumi show that chromium strengthens cast iron from 16.5 to 22.8 tons per sq. in. in an alloy containing 0.4 per cent of it without materially altering the structure.[38]

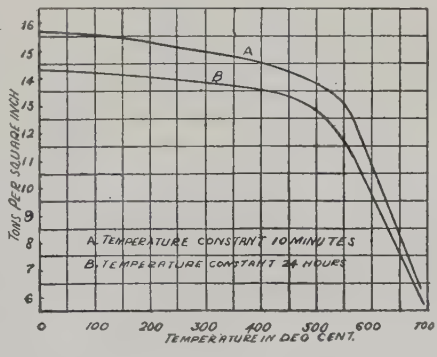

FIG. 32 TEMPERATURE-STRENGTH CURVE OF CAST IRON (20 PER CENT SEMI-STEEL)

(Figure reproduced from p. 421 of *The Foundry Trade Journal* of Nov. 15, 1923.)

CAST IRON AS AFFECTED BY HIGH TEMPERATURES

Cast iron is affected by high temperatures in two ways. In the first place, it has been found that cast iron when repeatedly heated and the heating is followed by cooling, increases in volume. This phenomenon occurs even at temperatures below the lowest critical point, i.e., below 725 deg. cent. (1337 deg. fahr.), and causes the formation of fissures which produce porosity in the metal. Another effect of heat is that cast iron when at a high temperature is apt to lose considerable of its strength.

Growth in Cast Iron. There have been a good many explanations of the causes of growth due to repeated heating and cooling. The most recent theories are (Okochi, Sato, and Kikuta) that the constitutional changes which occur at the critical points of heating and cooling set up considerable internal stresses, especially about the graphite flakes which are not subject to these changes. These stresses give rise to fissures and cavities in the neighborhood of

the graphite flakes and produce an increase in the volume. This volume increase can be accelerated in an oxidizing atmosphere by the penetration of the oxygen into these fissures. The theory of these Japanese workers does not explain, however, the phenomena of growth below the transformation point, of which there is abundant evidence, such as, for example, the oxidation effect of steam at temperatures not exceeding 425 deg. cent. (797 deg. fahr.).

According to J. H. Andrew and H. Hyman,[35] growth in cast iron takes place in two definite stages, the first or rapid stage being brought about by oxidation of the ferrite, with the carbon at first but slightly oxidized. When sufficient oxide has been formed, carbon becomes oxidized, with the result that the entire channels previously occupied by graphite become filled with oxide. Growth is always preceded by graphitization.

It has been found that within certain limits a higher silicon content is accompanied by greater growth. In fact, it is found that all the elements which, like silicon, precipitate graphite promote the increase of volume, while those elements which oppose the formation of graphite retard the process. Because of this, in cast iron where growth is objectionable, it is desirable to have a high manganese or chromium content (about 0.40 chromium), these elements forming stable carbides which resist changes. The formation of round graphite nodules instead of acute-angled flakes is also desirable.

Here it may be pointed out that cast irons low in total carbon have normally a very fine grain, and that on microscopic examination they show a highly divided graphite formed of very fine or curved lamellae, or of round nodules. This type of structure is frequent in semi-steel cast iron with high steel content (25 to 30 per cent), and particularly in cold and semi-cold blast metal.[29]

Strength at High Temperatures. Cast iron is superior to steel for such purposes as Diesel-engine and generally internal-combustion-engine cylinders, partly because of its better wearing qualities and also because of the greater facility with which complicated castings are made, which is due in part to the lower temperature at which cast iron has to be poured, its better ability to take the required shape, and also probably to the higher state of development reached by the cast-iron foundry as compared with the development of steel foundry.

The conditions of operation in internal-combustion engines, Diesel engines in particular, are such, however, as to submit cast-iron parts to considerable mechanical stresses at high temperatures. There have been a number of failures. An investigation by Arthur Marks[30] would seem to indicate that in bars which have been submitted to heating for 24 hr. at a constant temperature varying from 100 to 700 deg. cent. (212 to 1292 deg. fahr.) and then broken, the combined carbon at the center of the bar, where the fracture took place, showed no change. The breakage was therefore to

be regarded as not associated with change of constitution, i.e., the production of weak graphite by the decomposition of iron carbides, but to the natural reduction of cohesion at high temperature. From this it would appear that this is not so much a problem for metallurgical research as a case for the engineers who will have to reduce the temperatures to which cast iron is subjected below the quite reasonable one of 550 deg. cent. (1022 deg. fahr.). From this investigation it appears the strength varied as shown in Fig. 32, namely, from 14.4 tons (of 2240 lb.) per sq. in. at normal temperature to 13.1 tons at 505 deg. cent. (941 deg. fahr.), but fell to 8.9 tons at 600 deg. cent. (1112 deg. fahr.) and 6.8 tons at 700 deg. cent. (1242 deg. fahr.).

Another theory (André Levi) is that the increased volume following the first heat is due to decomposition of the cementite into iron and graphite, and the subsequent increase in volume is due to the combined effect of internal oxidation and the stresses produced in the metal at the transformation points.

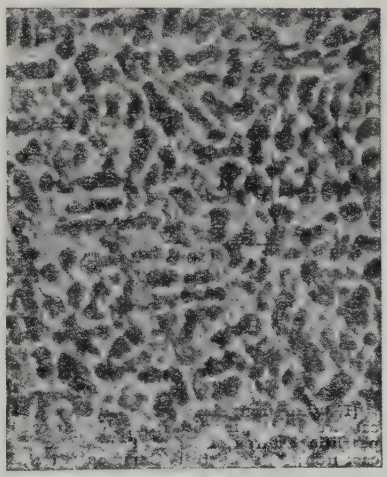

Fig. 33 Microstructure of White Cast Iron as Cast

(From Cast Iron in the Light of Recent Research, by W. H. Hatfield, Charles Griffin & Co., London, 1918.)

Contraction of Cast Iron. Cast iron is one of the very few materials which expand on freezing, thus filling out the mold particularly well. Then contraction takes place. Recent tests[31] have shown that the initial expansion in both white and gray iron is in direct relation to the gas content of the molten metal. It seems that the sudden decrease of the ability of the iron to hold gas in solution which occurs at the instant of freezing of the iron is the cause of the expansion of the iron, the gas being thrown out of the solution and mechanically stretching the iron out.

Tests with white Swedish pig iron showed expansion decreasing with the degree to which the metal was degasified by suction. Pig iron rich in manganese, which, when melted in the air, solidified with very considerable expansion, did not exhibit any expansion, if, upon being melted, it was held for a short time under a vacuum.

As regards contraction, the difference between white and gray iron is primarily limited to the pre-pearlitic part, during which the

secondary graphite is precipitated, while the post-pearlitic contraction is practically the same with gray and white iron. By regulating the rate of cooling, which means by controlling the temperature of the mold, it becomes possible to reduce the pre-pearlitic contraction to any desired extent or to eliminate it entirely. This makes it possible to eliminate the usual casting stresses and cracks in complicated shapes, and indicates another field where the application of metallurgical knowledge may bring important results.

Alloying elements may materially affect contraction phenomena by controlling the precipitation of the secondary graphite, it being

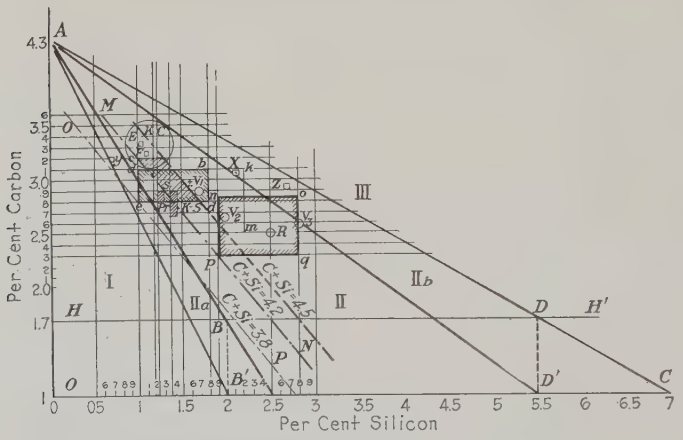

FIG. 33(a) PIEDBOEUF'S CAST-IRON DIAGRAM

[I, White iron; II, pearlitic cast iron; III, ferritic cast iron; II, IIb, III, gray cast irons; IIa, mottled iron; *K-C* (circle), Krupp cylinder iron; *F*, Bauer-Lanz pearlitic cast iron; *E*, Emmel's pearlitic cast iron (1924); *abcd*, LeThomas' pearlitic cast iron; *X*, semi-steel (Cameron); *crst*, Prache steel-cast irons; *Pr*, idem; *iklm*, Wüst & Bardenheuer's pearlitic cast iron; *nopq*, Thyssen-Emmel pearlitic cast iron; *R*, C = Si = 2.5 maximum strength, Thyssen-Emmel; *CD-MN*, limits of pearlitic cast iron, Lanz process (according to Buffet); *Y*, Lanz (Buffet) pearlitic cast iron; V_1, V_2, V_3, pearlitic cast iron (Varlet's experiments); *Z*, cast iron with pearlite and ferrite, Walter process].

generally found that the elements which assist the precipitation of the secondary graphite decrease the contraction, and those which hinder it increase contraction. This is why silicon, which promotes graphitization, decreases the contraction, while manganese produces an increased contraction through its opposition to graphitization.

Sulphur acts in a peculiar manner. In pure iron it decreases the contraction materially but in gray iron it promotes it rather strongly, because of its anti-graphitization action.

THE MAURER-PIEDBOEUF CARBON-SILICON DIAGRAM OF CAST IRONS

On page 116 there is a diagram developed by Dr. Edward

Maurer in which cast irons are classified by their carbon-silicon contents. As developed by Maurer the diagram was comparatively simple. Louis Piedboeuf's[40] diagram, however, shown in Fig. 33(*a*), is a far more developed form.

Maurer included in his diagram cylinder cast irons and Krupp special cast irons, and also the results of laboratory tests carried out by Wüst and Bardenheuer. Fig. 33(*a*) has been supplemented by points showing a whole collection of special irons, pearlitic irons, and semi-steels.

Point *F* corresponds to information given by Baurer in 1923 to characterize pearlitic cast irons obtained by the Lanz process. Few data have been published on their method. In a paper published in *La Fonderie Moderne*, Aug., 1925, M. Buffet, engineer of the Société Alsacienne, gives as the distinguishing feature of the Lanz pearlitic cast irons: C + Si = 3.8 to 4.2 per cent. The corresponding zone in the diagram is that included between the two parallel lines *OP* and *Mn*. Part of it comes within the space occupied by the mottled irons, i. e., those with an excess of cementite. This is quite as it should be, because, in the Lanz process, the pearlitic structure is obtained by heating the mold.

The circle *KC* circumscribes Krupp steam-engine-cylinder irons, and the zone *KS* the special high-tensile irons of the same firm.

Point *E* is derived from data published in 1924 by Emmel for pearlitic cast irons as produced by the Thyssen Company. These cast irons are distinguished by Si = Mn = 1.

The zone *crst* included between the lines C + Si = 4.2 and C + Si = 4.5, and the zone marked *Pr* differentiate two types of semi-steel cast iron as suggested by Lt-Col. Prache.

Point *X* indicates the composition of a special semi-steel cast iron used for aerial bombs, and suggested by Cameron.

The zone included within the rectangle *abed* is that of the pearlitic irons as produced at the Indret works, and as given in a very interesting paper published by M. LeThomas. The rectangle *iklm* is derived from the laboratory researches of Wüst and Bardenheuer.

The zone *nopq* is the region of cast irons produced by the Thyssen-Emmel process. These cast irons are said to give the best results from the point of view of evenness of texture and strength.

The points V_1, V_2, and V_3 indicate the results of a test made by M. Varlet (vice-president of the Belgian Association) at the foundries of the Société Esperance-Longdoz.

It may be presumed that the researches carried out by the Société Alsacienne tend in the same direction, since, in his paper quoted above, M. Buffet mentions the production of cast iron containing 2.3 and 2.5 per cent carbon.

Maurer's diagram clearly points out the advantage of low-carbon contents. The lower the carbon content, the wider the zone of pearlitic structure. There is thus greater certainty of getting the pearlitic structure without the risk of encroaching on adjacent

zones. By keeping at an equal distance from the cementite and ferrite zones, there is a greater chance of getting the pearlitic structure without heating the mold.

The same article gives a table showing the mechanical properties of various special irons (Bauer, Lanz, Krupp, Thyssen-Emmel, Kerpely, LeThomas, and Varlet).

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[39] Cp. also A. Wagner, Desulphurization and Reduction in Cupola Furnaces. *Stahl und Eisen*, pp. 1202–1205, 1925.

[40] Belgian Exchange Paper at the London Convention of the Institute of British Foundrymen, June 19, 1926, published in *The Metal Industry and The Iron Foundry*, vol. 28, no. 26, June 25, 1926, pp. 613–614 and vol. 29, no. 1, July 2, 1926, pp. 17–18.

CHAPTER VI

ALLOY STEELS

According to the definition adopted by the International Committee of the International Society for Testing Materials, alloy steels are "those which owe their properties chiefly to the presence of an element or elements other than carbon."

Thus steel containing, say, 0.30 per cent silicon is considered to be a carbon steel, while steel containing 3.20 silicon and developing certain special magnetic properties is called a silicon steel, is classed among alloy steels, and is extensively used in the construction of alternating-current transformers. There are many reasons why alloying elements are added to steels, and the action of some of them we understand fairly clearly, while the action of others is as yet quite obscure to us. We know, for example, why such an element as nickel is added to steel. The ultimate physical properties of carbon steels, as has been explained in Chapter IV, depend on the rate of cooling from the austenitic stage (from above the upper critical point Ar). If this cooling is extremely rapid as by quenching, the martensitic or troostitic stage is trapped and the metal becomes very hard. By cooling at slower rate the sorbitic stage is trapped, which gives the metal medium hardness and great toughness. Finally, by slow cooling the pearlitic stage is reached, and the metal is soft and highly ductile. It is obvious, however, that it is not always possible to achieve the first or second result. It is easy to cool quickly a thin piece of metal by quenching it in water, but if an attempt is made to cool in the same way a 22 × 22-in. ingot, the external layer will cool with extreme rapidity while the internal layer will stay hot for a very long time, and the result will be not a hardening of the ingot throughout but a hardening of the outside layer and gradual softening as we go inward, with a possibly soft heart. It is very likely also that the outside layer will be ruptured by the stresses induced by its effort to contract, while the inner part of the ingot retains its original dimensions. A judicious addition of nickel, however, produces structural changes in the steel which give a result equivalent to the quenching of a thin piece of steel, and we know fairly well the mechanism of this process.

How other alloying materials act we can merely conjecture. For example, extremely small additions of vanadium of the order of 0.1 per cent produce material changes in the steel and substantially increase its ability to resist alternating stresses. It is extremely unlikely that the minute quantities of vanadium distributed throughout the mass of the steel are capable of producing such changes by entering into direct combination with either iron or carbon, and the general feeling is that vanadium acts as a catalyzer, producing changes by its mere presence that are entirely out

of proportion to its mass. It is well, however, to remember that even if this surmise is correct, it does not really explain anything, because, even assuming that vanadium acts as a catalyzer, we have no information as to the reaction which it promotes.

It should be also clearly understood that some of the alloying elements are particularly valuable in that they either remove entirely or make harmless constituents which otherwise reduce the desirable properties of steel. Thus, the action of titanium is primarily to reduce the oxygen and nitrogen contents of steel and to impart to it thereby a closer grain structure. One of the reasons why zirconium is used in steel is to counteract the influence of the sulphur always present therein, and so on.

The steels with which the mechanical engineer has most to do are those containing as alloying elements nickel and chromium, singly or together, vanadium alone or in combination with the two others previously named, and the so-called "high-speed" tool steels characterized by substantial amounts of chromium and especially of tungsten. The mechanical engineer should, however, know something about the other alloy steels, as intensive research work is going on in many places and there is no doubt that many of the steels which have, relatively speaking, only a theoretical interest today, may become of practical importance in the near future.

Nickel Steel

This is one of the most important commercially of all the alloy steels. The introduction of nickel into carbon steel does not, according to some investigators, create a new constituent, although others have found that nickel and carbon form under certain conditions a carbide of the formula Ni_3C, which, however, breaks down very rapidly into nickel and free carbon. If nickel can replace some of the iron in iron carbide and then break down, this would account for the acceleration of graphitization due to the presence of nickel.

The most important effect of nickel in steel appears, however, to be in the direction of suppressing the transformation points. With low percentages of nickel all the critical points are lowered, and above 8 per cent nickel all the three points are united. We have seen in Chapter I that steel when passing through the Ar_2 critical point becomes magnetic and that this point for ordinary steel is located at a high temperature.

Nickel steels as well as nickel-iron alloys have a somewhat peculiar behavior in respect to the location of the critical points and appearance and disappearance of paramagnetism. If, for example, a 10 per cent nickel steel is heated, magnetism disappears at about 700 deg. cent. (1292 deg. fahr.). If now this steel is cooled magnetism does not reappear until about 400 deg. cent. (752 deg. fahr.). It has been noted before in this book, on p. 87, that the crit-

ical points Ar and Ac do not occur at exactly the same temperature, Ac being generally situated some 20 to 40 deg. higher than Ar. In the case of nickel steels, however, this difference between the Ac and Ar points may be as much as several hundred degrees. Up to a nickel content of 25 per cent the difference in temperature between the Ac and Ar points increases with the nickel content until at about 25 per cent of nickel the steel is non-magnetic even at 0 deg. cent. (32 deg. fahr.), but does become magnetic at lower temperatures. As the 25 per cent nickel content is exceeded the critical points at which magnetism disappears on heating and reappears on cooling gradually approach each other, until they come near merging. Steels in which there is the wide difference indicated above between the temperature at which magnetism disappears on heating and the temperature at which it reappears on cooling are called irreversible, while steels in which the two temperatures lie fairly closely together are called reversible.

There appears to be still some doubt as to whether nickel steel has superior resistance to repeated stresses. This is believed to be so by D. J. McAdam, Jr.[11]

Low-nickel or carbon pearlitic steels are formed with substantially the same structure as ordinary carbon steel, i.e., they consist of ferrite plus pearlite in the hypoeutectoid range, pearlite in the eutectoid range, and cementite plus pearlite above it, the only difference being that with the addition of nickel the eutectoid range is shifted to lower carbon-content percentages and is, for example, for 4 or 5 per cent nickel about 0.65 per cent carbon. When the nickel or carbon content is further increased, steels are obtained with the structure characterized upon ordinary unaccelerated cooling by either martensite or troostite, depending upon the amount of nickel. With still greater amounts of nickel, so great as to suppress completely the transformation point, the austenitic structure is preserved down to room temperature. Such steels are sometimes called "polyhedral," because of the appearance of their structure under magnification. (Compare Fig. 122 on page 319, no. 2, Metallography, by Samuel L. Hoyt, McGraw-Hill Book Co., 1921.) Industrially the most important are the pearlitic steels; the martensitic steels are somewhat like quenched carbon steel, i.e., hard and brittle, and therefore of little use; the austenitic steels may become of value when more about them is known, but the great cost of their production is a serious obstacle. The average effect of nickel in amounts up to 8 per cent is given as follows by Abbott:[20]

0.01 per cent of Ni increases the elastic limit 40 lb. per sq. in.
0.01 per cent of Ni increases the tensile strength 42 lb. per sq. in.
0.01 per cent of Ni increases the reduction of area 0.005 per cent
0.01 per cent of Ni decreases the elongation 0.010 per cent.

From this it would appear that little is to be gained commercially

by using nickel steel without previous heat treatment, and it is the latter that imparts to nickel steel its valuable properties.

The heat treatment to which nickel-carbon steel is submitted is usually limited to quenching from 850 deg. cent. (1562 deg. fahr.) and drawing at certain temperatures which vary.

The quenching should be from a temperature well above the critical range. Such a heat treatment increases the strength of the nickel steel enormously without materially lowering its ductility and toughness. It should be noted, however, that it is chiefly pearlitic steels with which the engineer has to do.

In these steels the percentage of nickel varies from 3 to 4 per cent. There is then another series of nickel steels with a very high percentage of nickel, of the order of 25 per cent, and carbon from 0.7 to 0.9 per cent. These steels have a great resistance to oxidation at high temperatures and are therefore used for valve stems for internal-combustion engines, low-temperature electrical-resistance wire, etc.

Two other alloys of nickel and iron are of interest, namely, invar, containing 36 per cent nickel and having a negligible coefficient of expansion at room temperature or slightly above it, which makes it valuable for the manufacture of measuring instruments; and platinite, having the same coefficient of expansion as glass and therefore used for lead-in wires in electric lamps.

Vanadium Steel

Because of its position in the periodic system of elements to the left of iron, vanadium has a great affinity for oxygen and carbon. It may therefore be used as a deoxidizer, but in addition it has in some way not yet clearly defined a degasifying effect on steel. Vanadium is capable of forming at least five carbides, depending on the temperature. The majority of these carbides are intensely hard. Because of this and also because of the very high price of vanadium no steels are made with more than 1 per cent of this metal, and even then the additions of vanadium are so proportioned that it is barely present in the final material, most of it disappearing by way of oxidation and otherwise in the manufacture of the steel. It does not appear that vanadium affects very materially the location of the critical points.

In structure, vanadium steel resembles carbon steel, except that when sufficient vanadium is present it produces what the French metallurgist Guillet called the "special constituent." This constituent appears in relief in the microsection beginning with additions of about 0.7 per cent of vanadium, and increases as the vanadium increases up to 3 per cent. Guillet believes that this special constituent is a carbide, as it is found only when carbon is present and increases in amount also as the carbon increases.

Vanadium in steel has one very important effect, namely, it apparently increases the ability of the steel to resist impact. It also

raises noticeably the yield point and tensile strength, but its effect depends very materially on the heat treatment the steel receives.

Manganese Steel

Iron and manganese form a continuous series of solid solutions as shown by the constitutional diagram laid down by Rümelin and Fick,[16] the liquidus and solidus falling very close together. Contrary to what happens in the case of a simple binary eutectiferous system such as shown on p. 9, the freezing of an iron-manganese alloy proceeds in the following manner.[17] The velocity of crystallization of the molten metal is so great that solid solutions are simultaneously established with different contents of manganese. Because of this crystals appear in the metal which are differently affected by etching reagents. It is also important to remember that manganese is chemically so close to iron that it may replace the latter without going into chemical combination with it. Manganese in manganese steel behaves exactly like the iron. It unites with it to form a "ferrite," and like iron takes up carbon to form carbides.

The effect of manganese on the critical points of steel was determined by Wüst, who found that every one per cent of manganese up to about 5 per cent lowers Ar_1 by 20 to 25 deg. cent. (36 to 45 deg. fahr.) and that the hysteresis is increased by a slightly greater amount. Above 5 per cent manganese no heat effect was noted on cooling. Rümelin and Fick, however, found the heat effect at 816 deg. cent. (1501 deg. fahr.) from 1 to 50 per cent manganese, and another over the same range falling from 767 deg. cent. (1412 deg. fahr.) to 711 deg. cent. (1312 deg. fahr.).

There are really two manganese steels. One is a pearlitic manganese steel. Since manganese forms a double carbide with cementite, the effect is to increase the tensile strength of the metal. Manganese steel containing 0.45 to 0.55 per cent carbon with about 1.25 per cent manganese has been successfully used in a heat-treated condition for rifle barrels. D. R. Bullens[18] claims that when properly made and suitably heat-treated, lower-carbon pearlitic manganese steels are not brittle, but the manganese appears to make the steel more sensitive to ill treatment. The other kind of manganese steel, much better known, is the so-called Hadfield high-manganese steel containing anywhere from 8 to 14 per cent manganese and specially heat-treated by quenching it in water from 900 to 1100 deg. cent. (1652 to 2012 deg. fahr.). This is so hard that it cannot be machined or drilled, and yet it may be indented by a hammer. It also possesses a peculiar flowage when used in crushing machinery. While it cannot be machined, it can be forged, but when this is done care must be taken not to overheat the metal. The first characteristics of manganese steel appear to be, however, its resistance to abrasion and its ability to deform plastically.

High-manganese steel has no critical points, so that in heat treatment the operator has to be guided by the relation of the carbide to the physical properties. Silico-manganese steel with 0.5 to 0.7 manganese and 1.25 to 1.50 silicon is used in tempered gears and springs. It has the disadvantage of being very sensitive to heat treatment. Upon suitable treatment it gives a tensile strength of from 195,000 to 230,000 lb. per sq. in. It is said to be used extensively in France and Germany, but less so in this country.

Chromium Steel

Chromium is used so extensively in the production of alloy steels

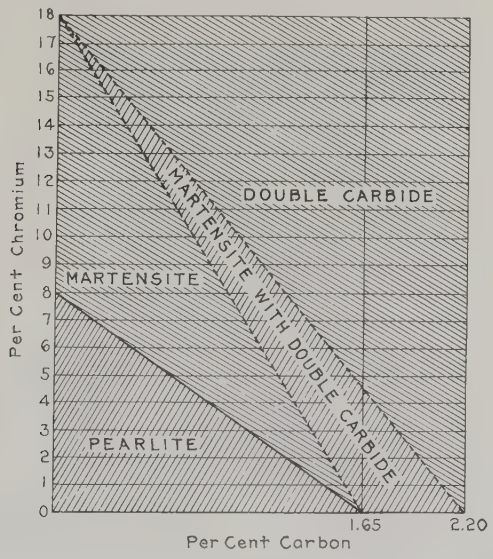

Fig. 34 Structural Diagram of Chromium Steel

and is so important in its action that it has been referred to as one of the key metals, i.e., metals vitally essential to the development of the industry. It may be used either alone, in which case it profoundly modifies the properties of ordinary carbon steel, or together with other alloying elements, such as nickel, tungsten, cobalt, vanadium, molybdenum, etc.

In the periodic system of elements chromium is located to the left of manganese and has therefore reactions with iron quite similar to those of manganese. It alloys with iron in all proportions and forms solid solutions. There are also indications that iron and chromium are capable of forming a chemical compound or compounds which profoundly affect the physical properties of the alloy. Chromium has also a very high affinity for car-

bon, forming with it several carbides remarkable for their hardness, ability to persist at very high temperature, and close crystallization. Chromium appears also to be capable of holding carbon in solution. As regards its influence on steel, it would appear that chromium in steel has the ability of opposing both the disintegration and the reconstruction of cementite, thereby producing changes in the critical points of steel, raising the Ac range and lowering the Ar range.

The microstructure of chromium steels was studied by Guillet, who worked out the diagram shown in Fig. 34.[35] From this it would appear that chromium steels, depending upon the chromium and carbon content, may be pearlitic, martensitic, carbide-martensitic, and of the pure carbide type. It would appear, moreover, that the carbide present in the composition of these steels is a double carbide of iron and chromium, and that the carbide-martensitic steels are a transition product.

Because of the very high critical points of chromium steels they must be forged at a higher temperature than carbon steels of similar carbon content, and should it happen that the forging has been carried out at a temperature below the critical, chromium steels have to be subjected to a longer and more powerful anneal than carbon steels. There seem to be, however, reasons to believe that what Guillet refers to as martensitic steels are not true martensitic steels.

Essentially, chromium steels behave in respect to slow anneal and rapid quench at high temperatures like the carbon steels. In annealed steels, carbides are predominant either in pearlitic form or as free carbides. The stable martensitic or polyhedral structures can be obtained only by very rapid cooling or quenching.

Unfortunately, comparatively little is known about the carbides present in chromium steel. Osmond claims that chromium in chromium steels may be present in one of the following three states: namely, as a solid solution of metallic chromium, as a combination with iron and carbon in the form of individual globules of carbide, or as the same carbide but in solid solution. Murakami[1] believes that there are three ternary carbides of iron, chromium, and carbon, and that the hardness of chromium steels is due to the presence of a solid solution of the carbide Cr_3C_2 in a solution of iron and carbon.

It is important to remember that in addition to this, chromium and iron form a compound or combination which is generally referred to as "chromium ferrite" corresponding to the alpha iron in carbon steels.

According to Hoyt[2] the effect of the first additions of chromium is to make the steel finer grained and to disseminate the carbon. With further additions of chromium the steels resemble quenched carbon steels and contain martensite and troostite. Next comes the transition zone between the martensitic steels and the carbide

steels. In this range chromium is added without materially affecting the microconstituents, the principal effect being a retardation of the crystallization of both ferrite and pearlite. More chromium produces a structure of hardened steels. On further increase in the chromium, the predominant martensite begins to disappear and polyhedra appear containing traces of fine-grained martensite in their interiors. Increasing the chromium still higher, up to 18 per cent and above, gives a polyhedral structure containing the carbide as small white crystals but exhibiting no martensitic structure. Steels with 0.8 per cent carbon are pearlitic up to about 3 per cent chromium. From 3 to 9 per cent chromium, a dark constituent (on etching) resembling troostite is present. A further increase of the chromium produces martensite as before, until with the final appearance of the martensite the steels show a polyhedral structure with white, structureless crystals, the carbide.

Thus far we have been dealing chiefly with the influence of chromium on the structure of the metal and its mechanical properties. Chromium has, however, another influence, and this is the increasing of the acid resistance of steels.[24] This takes place in two ranges, within which the steel acquires what is known as the property of "passivity." According to Tammann,[3] ordinary iron becomes passive under certain conditions, as, for example, after immersion in nitric acid, through the fact that each iron atom on its surface is combined with an atom of oxygen and hence its connection with the iron atoms located below it has been interrupted. Mechanically, however, the film of oxidized iron does not adhere solidly but peels off and exposes to atmospheric and acid influences the rest of the metal. The chromium atoms stabilize this surface skin. As the content of chromium increases from 4 to 14 per cent the corrosion resistance of the carbon-free alloys with respect to dilute nitric acid increases very rapidly. From 14 to 20 per cent chromium this resistance increases rather slowly. This led to the development of the so-called "stainless" steels containing from 0.10 to 0.20 per cent carbon and from 10 to 14 per cent chromium, and stainless irons with approximately the same content of chromium but an even lower content of carbon. The value of these steels lies in the fact that when polished they are practically unaffected by organic acids. They are claimed also to have shown a high ability to resist erosion such as is encountered in the blades of steam turbines.

An extensive program having to do with the effect of elevated temperatures of stainless iron and some other materials is now in progress at the Westinghouse Research Laboratory, sponsored by the South Philadelphia Works. Both "short-time" and "long-time" tests of stainless iron in the annealed and in the quenched and drawn states are being made. Results of "long-time" tests completed to date indicate that annealed stainless iron is susceptible

to considerable strain hardening, and this is relieved but very slowly, if at all, at temperatures of 750 deg. fahr.; further, that specimens held under loads up to the proportional limit and at temperatures up to 750 deg. fahr., show no additional deterioration with the time element. This work will be the subject of a joint report at a later date.

Tests to judge the resistance to corrosion have been made on practically all of the materials referred to. Cylinders, disks, and portions of forgings have been subjected to the action of steam, heat, running tap water, salt water, salt spray, stagnant water, atmosphere, and the elements, dilute and concentrated acids, magne-

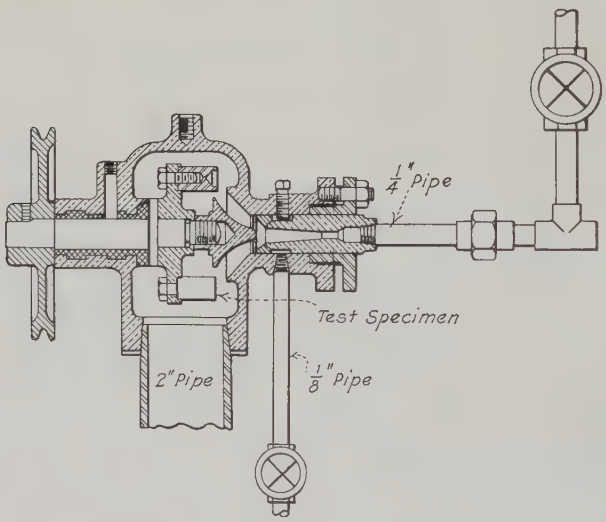

Fig. 35 Sketch of Corrosion and Erosion Test Apparatus

sium chloride, calcium chloride and some other conditions. Such tests, in the absence of definite standards, can only serve to indicate the general behavior and for the present purpose, general results or conclusions will be given rather than many meaningless figures. The general indications are:

1 That heat treatment which is so essential to bring out the resistance to corrosion in the higher-carbon stainless steel, appears entirely unnecessary with stainless iron.

2 That alloys of increasing chromium content, and especially those of high chromium content containing silicon, appear to offer more marked resistance than the low-chromium alloys.

3 That increased silicon gives greater resistance to scaling.

4 That the addition of 1 per cent copper appears to increase the resistance of salt water or spray.

5 That a properly prepared pickled surface is quite resistant to actual corrosion, although it may show some superficial rust. A case in mind is that of a forging with an improperly prepared pickled surface being left on an outdoor scrap pile for several weeks. A coating of rust appeared all over. Leaving one third of the surface in this rusted state, a second third was properly pickled, and the other third polished. After being outdoors subject to the elements for nearly two years, the rusting of the original third has progressed no further and the other portions are without change.

Of especial interest to many is the resistance of these materials to the corrosive and erosive action of wet and dry steam under varying conditions up to 750 deg. fahr., with and without foreign or other matter which would accelerate either action. Fig. 35 shows a small machine for the purpose of making a study of this matter, which study is now in progress. It consists of a steam-tight casing in which a shaft is revolved by means of a pulley, driven by a motor not shown. The shaft at its opposite end carries a disk and deflector, with ten specimens secured to the disk as shown. Steam or water entering by means of the nozzle is deflected against the sharp edges of the specimens. A second nozzle, not shown, permits of the steam or water impinging directly on the specimens without the use of the deflector. Both nozzles are provided with an injector arrangement permitting the introduction of any chemical or gas into the steam or water. The purpose of revolving the specimens is to secure uniform subjection of all specimens to the corroding or eroding medium, something which is often unaccomplished in many corrosion tests. Stainless iron is being examined extensively in this way, and the results will be available at a later date.

The hot working of stainless steel requires more than ordinary care, but the alloys in general may be cold rolled, drawn, upset, pressed, and otherwise cold worked. Experience has shown that the amount of work between anneals and the speed of working are greatly reduced over soft carbon steel, and the wear on rolls, dies, or other tools greatly increased. Where expedient, cold rolling is practiced in preference to cold drawing. For annealing, dead-softness will result by heating to 1800 deg. fahr. and cooling very slowly; but for most cold-working operations, annealing at 1400–1500 deg. fahr. and cooling in the furnace or air will be sufficient.

Another development along the same line is the production of heat-resisting chromium steels containing from 22 to 28 per cent chromium (Becket metal, Duraloy, Fahrite, etc.) and a variable content of carbon from 0.2 to 1 per cent (the lower percentages of carbon are used in pieces that have to be machined and the higher in those where excessive hardness is not objectionable). While the mechanical properties of these very high-carbon steels apparently are no better than those of corresponding straight carbon steels, they have an extremely high resistance to oxidation at high temperatures and may be repeatedly heated for very long periods at

temperatures as high as 1800 deg. fahr., and in some cases 2000 deg. fahr.

Chromium steels of the following compositions are used.[4] Carbon up to about 0.35 per cent and chromium of about 0.5 per cent are employed where the steel has to be case-hardened. According to E. W. Ehn,[5] the chromium does not really affect the ability of steel to take the case but insures that the steel is free from oxides, and it is this freedom that is important in order to produce effective case-hardening. The same content of chromium with carbon between 0.35 and 0.50 gives after heat treatment about 15 per cent increase in tensile strength and 10 per cent increase in elastic limit with practically no loss in ductility as compared with straight carbon steels of the same carbon content. With the same content of chromium and high contents of carbon (up to about 1 per cent) the hardness increases still more. This kind of steel is extensively used for well bits and jars, drills, razors, etc. Chromium steels containing from 1.00 to 1.75 per cent chromium with carbon ranging from about 1 per cent up give some of the most important straight chromium steels. These are used in balls and races of ball bearings, crushing machinery, safes, tools, etc. The great advantage of this steel is that it can be made soft by annealing, say, 150 Brinell, and then can be hardened without distortion to 600 Brinell and over. The degree of hardness depends upon the distribution of the chromium-iron carbide, which is in turn controlled by the temperature-time elements in the heating and cooling phases. Chromium steels with about 2 per cent chromium are used in the manufacture of armor-piercing projectiles, crushers, cold rolls, drawing dies, etc.

"Flakes" or "Hair-Cracks" in Chromium Steel.[25] Internal cracks have appeared in large-sized bars and forgings of high-carbon chromium steel for ball and roller bearings. The formation of flakes has been studied by rolling, and forging experiments have been carried out under varied conditions. It has been found that such flakes, when present, invariably formed during cooling after the final hot-working operation, and that their formation is prevented by retarded cooling. The defects may therefore be designated as "cooling cracks," and it is possible to retard the cooling so as to prevent the formation of flakes, and at the same time avoid the undesirable effects of slow cooling on the structure and on the physical properties of the steel.

Chrome-Nickel Steel

It is significant of the rapidity with which modern metallurgy has developed that chrome-nickel steels, which are such a vital element in the construction of modern machinery, especially automobiles, were first described by Guillet in 1905 in a paper before the Iron and Steel Institute. They were used for a considerable time previous to that, however.

Chromium and nickel when used jointly in steel and when properly treated appear to have the beneficial effects of both the chromium and the nickel without the disadvantages which are inherent in the use of either one separately. According to Dumas,[6] chromium produces a lowering of the critical points in irreversible nickel steels (nickel content under 25 per cent) and a rise of the critical points in reversible nickel steels. According to Guillet,[7] five different structures are encountered in chrome-nickel-steels: namely, pearlitic with ferrite or carbide, purely martensitic, martensitic with inclusions of carbide, polyhedric, and polyhedric with inclusions of carbide. The transition from pearlitic to martensitic structures depends on the joint content of carbon, nickel, and chromium. An addition of chromium to martensitic nickel steel produces a formation of a certain amount of carbide and the appearance of polyhedra. In polyhedric nickel steels the addition of chromium produces a formation of carbide.

According to Hoyt,[8] chrome-nickel steels may be classified into three types which contain the following percentages of nickel and chromium: (1) nickel 0.5, chromium 0.7; (2) nickel 3.0, chromium 0.6 to 0.9; (3) nickel 3.5, chromium 1.5. Each type is used generally with three different carbon contents: (*a*) low carbon for case-hardening parts; (*b*) 0.35 carbon for shafting and similar parts; (*c*) 0.50 carbon for heat-treated gears, crankshafts, and transmissions of automobiles, motor trucks, etc. The critical points of these three grades of steels have been determined by the Bureau of Research of the Midvale Steel Company. The correct temperature for the final quench would be about 25 deg. cent. above the upper line.

In general the chrome-nickel steels are very similar to the nickel steels; but (*a*) they have higher elastic limits with about the same ductility; (*b*) they are harder than the nickel steels, especially when heat-treated; (*c*) they are more susceptible to heat treatment, and many of them harden considerably when cooled in the air; and (*d*) they possess dynamic toughness and resistance to fatigue stresses in the highest degree, when properly treated; and on account of these properties they are not surpassed, as construction steels, by any other steels. It is interesting to note that the static properties of the low-nickel, low-chromium steels are nearly the same as those of high-nickel, high-chromium steels. However, the latter type is generally to be preferred for parts which are subjected to exceptionally severe service.

The low-chrome-nickel steels are less expensive than either the high-chrome-nickel steels or the $3^1/_2$-per cent nickel steel, and are therefore very generally used in sections up to one and one-half inch round for parts which require high static properties but which do not require all that can be given in toughness and dynamic properties. They may be readily heat-treated to give the following properties: tensile strength 130,000 lb., elastic limit 105,000 lb.,

elongation 16 per cent, reduction of area 52 per cent, Brinell hardness 275, scleroscope hardness 47; or tensile strength 220,000 lb., elastic limit 185,000 lb., elongation 9 per cent, reduction of area 30 per cent, Brinell hardness 390, scleroscope hardness 62.

The impact resistance of nickel-chromium steel[36] was found to vary according to the type of fracture obtained. Four samples, showing silky fibrous, crystalline, slightly reedy, and very woody fractures, respectively, and with 0.33 to 0.40 per cent carbon, 1.35 to 1.68 per cent nichrome, and 0.55 to 1.60 per cent chromium, were cut into standard Izod-test specimens. The latter were quenched in oil from 325 deg. and tempered at various temperatures between 150 and 540 deg. followed by air cooling, and were tested for impact resistance and Brinell hardness. With tempering below 370 deg. the hardness curves were irregular and all the impact fracture were crystalline. The "silky fibrous" sample showed the best impact resistance, and the "crystalline" and "woody" samples the lowest. The Brinell hardness gives no indication of brittleness. The character of the steel as shown by the fracture wsa constant, regardless of heat treatment. A short bibliography is given in the original paper.

As regards the heat treatment of chrome-nickel steels and their mechanical properties, further information may be found in D. K. Bullens' book on Steel and Its Heat Treatment[9] and especially in an article by H. J. French.[10]

Molybdenum Steel

This is one of the comparatively new classes of steel and one on which more knowledge is desirable. It is not clear yet, for example, exactly how the introduction of molybdenum into steel affects the microstructure and location of the critical points. The general belief is, however, that the addition of small amounts, 0.20 to 0.75 per cent, of molybdenum to plain carbon, chromium, nickel, or chrome-nickel steel makes it possible to obtain by suitable heat treatment either higher elastic limit with the ductility, or higher ductility and especially a greater reduction of area at the same elastic limit; that such steels show greater depth of hardening (i.e., more uniform hardness throughout large sections); that they have a wide range of effective hardening temperatures, variation of which does not greatly alter the mechanical properties; and that to secure equivalent softening on tempering with other analogous steels, the draw temperature must be higher.[12] On the other hand, it is claimed that[13] one of the difficulties with molybdenum steel is its tendency toward dissociation, producing at times a badly balanced steel with foreign inclusions, difficulty in fabrication, and bad test and surface results.

In plain carbon steel molybdenum produces some improvement when the steel is heat-treated. In steel merely normalized molybdenum produces no improvement and may even make the steel

worse. A comparison of chromium-molybdenum and chromium-vanadium steel, it is said, shows that there is no appreciable difference in physical properties between the two steels, and that 0.40 per cent molybdenum comes very close to giving practically the same results in a chromium steel as that obtained by the addition of 0.2 per cent vanadium. By increasing the molybdenum up to about 0.80 per cent the tensile strength may be raised without very great loss in ductility.

Hoyt presents the following figures which were obtained by the United Alloy Steel Corporation with a chrome-nickel-molybdenum steel such as was used for Liberty-engine crankshafts. The composition was: C 0.30; Mn 0.69; Cr 0.98; Ni 3.05; Mo 0.54. The bar was annealed at 1600 to 1605 deg. fahr., cooled in air, treated at 1475 deg. fahr. for half an hour and quenched in water, and then drawn at 1150 deg. fahr. for two hours and cooled in air. The figures given for this steel, taken from a publication of the Climax Molybdenum Company, are: elastic limit, 130,000 lb.; tensile strength, 142,000 lb.; elongation on two inches, 20.5 per cent; reduction of area, 65.0 per cent; Brinell number, 303; and Izod impact number, 67.

The advantages of these steels may be summed up somewhat as follows: (1) They can be produced with exceptionally high elastic limits without sacrificing ductility and toughness; (2) the quenching and tempering ranges are particularly large; (3) when annealed the steels are soft and easily machined; (4) when in the heat-treated condition the elastic limit can be left exceptionally high without sacrificing machinability. This latter point has particular significance in the commercial production of high-grade machine parts.

Gillett and Mack[14] also present data on a nickel-molybdenum steel containing 0.3 per cent carbon and 0.62 per cent molybdenum, and on several chrome-nickel-molybdenum and chrome-nickel-vanadium steels. A detailed study of the effect of molybdenum in nickel steels was recently made at the Woolwich Arsenal, England, on specimens cut from large forgings transverse to the direction of the forging. These tests, with some reservations, proved to be favorable to the molybdenum steel.

Molybdenum in high-speed steel did not prove successful and a cobalt-molybdenum high-speed steel containing no tungsten gave very poor results. On the other hand, molybdenum has been successfully used for automobile parts (Wills-St. Claire, and Studebaker cars), crankshafts of the Liberty motors made during the war by the Ford Motor Co., in blooming-mill rolls, forging dies, etc. Summing up the whole situation, it would appear that molybdenum does not accomplish anything that cannot be attained by the use of other metals, especially vanadium, but that there is a hope that molybdenum steel for the same effect will be cheaper than vanadium steel. Furthermore, some metallurgists are con-

vinced that at the same cost as competing steels, there is a saving in the use of molybdenum steels due to the ease with which they are forged, heat-treated, and machined.

An automobile producer compared two lots of steering knuckles, totaling 20,000, made respectively from 0.30 per cent C, 1.25 per cent Ni, 0.60 per cent Cr; and from 0.30 per cent C, 0.20 per cent Mo, 0.60 per cent Cr. Both steels were heat-treated to 270–320 Brinell. The number of pieces machined per grind of tool, averaging all the operations of drilling, reaming, tapping, turning, etc., was over twice as many on the chromium-molybdenum as on the chromium-nickel. A similar comparison made on axle shafts showed a 36 per cent advantage for chromium-molybdenum. Still another comparison showed that chromium-molybdenum steel of 325 Brinell hardness machined as well as $3^1/_2$-per cent nickel steel of 270 Brinell hardness. On the two steels, heat-treated to the same tensile strength and Brinell hardness, the time of drilling, milling, and reaming was found to be about half as great with chromium-molybdenum as with $3^1/_2$-per cent nickel.

Other tests do not show so great an advantage for molybdenum steels, but the weight of evidence indicates that the machining properties of these steels constitute a real advantage.[15]

Carbon-free alloys of iron and molybdenum have been investigated by W. P. Sykes,[37] who, among others things, gave an equilibrium diagram of this system. Notable features of the system include a eutectic at 36 per cent molybdenum melting at 2625 deg. fahr., a glass-hard intermetallic compound Fe_3Mo_2 at 53.4 per cent molybdenum, and appreciable solid solubility, increasing with rise in temperature at either end of the system. The critical point Ar_4 is lowered by the addition of 3 per cent of molybdenum to pure iron from 2550 to 2245 deg. fahr. and Ar_3 is raised to 1795 deg. fahr. With the molybdenum content greater than 3.5 or 4 per cent the iron exists in the body-centered crystal lattice at all temperatures below the melting point. Among other things, it has been found that iron-molybdenum alloys are subject to aging and, for example, by aging the quenched alloy at 1155 deg. fahr., the tensile strength is increased from 58,000 lb. per sq. in. before aging to about 150,000 lb. per sq. in. after aging. Hardness also may be increased by aging, but a decrease in ductility accompanies the increase in tensile strength.

Uranium Steel

Several statements have been made to the effect that steel to which uranium has been added possesses particularly high resistance to shock and is therefore of value for such purposes as armor plate. The great difficulty in producing uranium steel is the excessive loss of uranium in the making of the alloy, especially when attempts are made to add a high percentage of uranium, say, 5 per cent or more. There is also often marked segregation of uranium

between the top and the bottom of the ingot. Uranium oxidizes very easily and therefore is easily lost. Keeney[21] states that steel makers using ferrouranium containing 15 to 30 per cent of uranium could not make the uranium stay in high-speed steel. J. A. Mathews[22] claims that while uranium has been proposed for use in high-speed tool steel, it is difficult to handle owing to the ease with which it is oxidized, and that steel to which it is added is more apt to show seams and defects than steel from which it is absent.

Boron Steel

From all indications boron steel seems to be a very remarkable material of which little is known and on which less work has been done than it has deserved.

Several batches of boron steel were made up at the Bureau of Mines laboratory[23] and at the Bureau of Standards. The samples contained variously from 0.09 to 0.7 per cent boron. When the ingots were heated to the usual temperature for hot rolling the material was so brittle that it fell apart of its own weight. When the preheating temperature was materially lowered it became possible to roll the metal, but it still seemed to possess a considerable brittleness when hot (hot-shortness).

A very remarkable feature of the boron steels is that while the steel is freezing in the mold it has for a long period a peculiar consistency. As the molten metal starts to cool it is at first like molasses, then like dough or modeling wax. When the top of the ingot within the hot-top is poked to keep the hole open into the pipe for the escape of gas, the steel can be poked into any shape desired and the shape will be retained, just as in the case of pie crust when the border is fluted with the thumb.

This plasticity is retained far below the solidifying point of ordinary steel, apparently down to approximately the melting point of cast iron, or even below. It is probable that boron forms a very low-melting eutectic with carbon, so that the range between the liquidus and solidus of a steel containing boron is enormously increased, which would account for its plasticity. Boron also appears to confer marked hardness on steel. There is a good reason to believe that when more is known about this steel and its properties are better controlled, a method will be developed for pressing out of it such parts as gears, etc., especially where these parts are to be subjected only to moderate strains.

According to W. Freytag and W. Jenge,[26] the tendency to pipe is decreased by additions of boron, but more than 0.8 per cent boron renders the metal brittle and unworkable, a state which is also brought about in steels of lower boron content by quenching. Boron increases hardness considerably. This effect is noticeable with 0.1 boron in steel containing 0.3 per cent carbon, but not until 0.5 boron has been added to steels of higher carbon content.

Examination of the microstructure of the metal indicates that in hypoeutectoid steels the boron goes into the pearlite, increasing its amount and giving it an appearance similar to that of the cementite.

Ferroboron[27] may be prepared from boric acid by reduction in a fused bath of iron by means of carbon, silicon, or aluminum. In this way an alloy was obtained containing over 18 per cent of boron which can be used in making boron steel.

Cerium Steel

While in cast iron cerium increases the transverse strength and deflection, the metal freezing more slowly than untreated metal and giving less combined carbon, in steel it apparently increases the uniformity of structure. From tests made at the Bureau of Mines[3] it has been found that the ferrite network usually formed by manganese sulphide inclusions is absent in the cerium-treated samples. Bars taken from the lower part of the castings made from cerium-treated steels were cleaner and showed marked superiority in ductility. It is not known that any cerium steel is available in the market. Considerable work has been done, however, in utilizing cerium and cerium-lanthanum for the purpose of purifying steel by desulphurization and deoxidation. Cerium to the extent of 0.1 per cent has been used successfully for the deoxidation of monel metal. It does not appear that it is uniformly effective in steel, but it does appear that under certain conditions cerium acts as a desulphurizer. On the other hand, however, cerium steel has a dirtier appearance than steel without cerium and shows numberless tiny inclusions supposed to be cerium-oxide spots.

Zirconium

The effect of zirconium on the hot-rolling properties of high-sulphur steels has been described by A. L. Field,[28] who finds that zirconium combines with the sulphur of molten steel, forming a zirconium sulphide; zirconium completes the deoxidation of the steel before proceeding to combine with the sulphur.

Tellurium Steel

Examination of a steel containing 0.12 per cent tellurium[29] shows a presence of a non-metallic constituent, probably a telluride closely associated with manganese sulphide. When the steel is forged this telluride does not break up but elongates fully as well if not better than manganese sulphide. The steel is lower in ductility than normal material without the tellurium. It forges well and gives no evidence of red-shortness. There is a possibility that tellurium might be used instead of sulphur to improve the free-cutting or free-machining properties of steel.

Acid-Resisting Silicon Irons

These are hypoeutectoid steels, with a maximum carbon content of 0.80 per cent. Because of their hardness, they cannot be machined, but have to be used as castings only. These iron are primarily distinguished by their very high silicon content. It has been found that as far as resistance to action of acids is concerned, a silicon content of less than 12 per cent is ineffective. But the silicon is usually kept between 13 and 15 per cent. Metallurgically these alloys are solid solutions of iron-silicide and iron, the combination in which the carbon occurs being somewhat uncertain.[34]

Cobalt Steels

These are extensively employed for the making of permanent magnets,[30] as they increase greatly the specific magnetism. Tests have shown, however, that in addition to the cobalt content the coercive force also depends upon the other ingredients and the carbon content, as well as on the care with which the annealing has been carried out.

Medium-alloy steels of high cobalt content are extremely brittle in the annealed state and considerable care is necessary in machining. Air-hardening high-alloy steels are tough and strong and easily machined. Cobalt magnet steels contain from 20 to 60 per cent cobalt, 0.3 to 2.0 per cent carbon with either 0.5 to 20 per cent tungsten, 0.2 to 15 per cent molybdenum, or 0.3 to 10 per cent chromium. Because of the very high price of cobalt, tungsten or chromium steels are preferably used wherever possible.

Opinions differ as to the influence of cobalt and vanadium in high-speed steel.[31] Certain tests have shown that cobalt produces improvements only when used in conjunction with vanadium additions, also that cobalt improves the forging qualities of molybdenum steels. Other comparative hardness and cutting tests[32] show that the presence of 5 per cent cobalt (optimum cobalt content) does not improve the cutting properties of high-speed tool steels to any great extent, but greatly facilitates thermal treatment by allowing a lower quenching temperature.

High-Speed Tool Steel

The progenitor of the modern high-speed tool steel was the Mushet air-hardening steel containing $1^1/_2$ per cent carbon, $^1/_2$ per cent manganese, and 7 to 8 per cent tungsten. In the beginning of the 90's chromium was substituted for manganese, which produced a steel containing 1 per cent carbon, 0.2 per cent manganese (Midvale Steel Co.), 2 per cent chromium, and 8 per cent tungsten. From 1894 to 1898 Taylor and White in connection with their investigation into the cutting of metals developed at the Bethlehem Steel Co. their famous high-speed tool steel which, at that time, contained $1^1/_2$ per cent carbon, 4 per cent chromium, and 8 per

cent tungsten, and was subjected to a complicated heat treatment. It was later found that the heat treatment which they employed could be simplified a good deal and that better results were obtained by increasing the content of tungsten to between 13 and 18 per cent and by reducing the carbon to from 0.4 to 0.9 per cent. Later, cobalt was substituted in part for tungsten.

According to Guillet,[19] high-speed tool steel, depending upon the amounts of carbon, chromium, and tungsten, has the following microstructure: pearlite, martensite, martensite plus carbide, carbide in gamma iron, and carbide in troostite. In later investigations it was found that in order to obtain the best steel the sum of the carbon, chromium, and tungsten content must be high so that neither pearlite nor martensite forms on slow cooling, while the chromium must not be too high in order to prevent the formation of gamma iron. The end sought in high-speed steels of certain compositions on quenching is to avoid gamma iron and to produce fine-grained martensite containing no carbide.

The mechanism which would account for the cutting properties of high-speed steel and the part played in it by chromium is as yet quite uncertain. What is known, however, is that the hardness of a piece of high-speed tool steel as measured, for example, by the Brinell number, has very little to do with its ability as a cutting material. As early as 1905 Taylor pointed out the vast difference between hardness at room temperature and hardness and ability to retain hardness at a dull-red heat. The only method for judging high-speed steel is therefore the lathe test.

Chromium[33] increases both the hardness and the toughness of high-speed steel. It increases the amount both of austenite and of martensite found at lower temperatures and particularly the amount of austenite retained after a 2400 deg. quench. This gives steel very great toughness and makes it suitable for certain work where the tools are subjected to great shock. Tungsten alone in the steel quenched at very high temperatures causes a marked hardness which, however, is accompanied by brittleness. Chromium increases the hardness throughout at all quenches and draws, and it seems likely that its presence may assist in the solution of tungsten in the austenite solid solution. Moreover chromium reduces the oxidation and scale of the steel enormously during heat treatment and is said to assist in the welding of tungsten in the crucible.

Vanadium was found to improve steel, apparently by cleansing it, but the addition of $^1/_2$ per cent of vanadium, from which great things were expected, did not prove greatly important. The introduction of cobalt (about 5 per cent) is said to give tool steel a more uniform performance, i.e., ability to work very well on mild steel, special steels, or cast iron. Additions of molybdenum do not produce a good material, while for uranium claims have been made which so far have not been entirely proved.

In discussing the chemical composition of tool steels, J. P. Jill

and M. A. Frost[38] arrive at the following interesting conclusion:

"Any effort at this time toward the standardization of tool-steel specifications by any buyer or organization is detrimental to the best interests of all. Because of the wide range in composition; the satisfactory substitution of one alloy for another; the detrimental effect of small amounts of many elements; the inclusion of oxides and dirt; and the effects of grain size and structure, no purchaser can draw up a specification that would meet commercial practice that would fully protect him from obtaining an undesirable tool steel. The purchaser's best protection is the brand name, as it is the quality mark of the manufacturer. The deserved reputation of a brand is highly prized by the maker, and he will in no way jeopardize that reputation by selling an inferior product under that brand name.

"No industry has been more free in the employment of technical skill than the tool-steel manufacturers, yet the making of tool steel is still an art, and this is as true today as it was in the time not long ago when the secrets of the trade were handed down from father to son."

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CHAPTER VII

FORGING

Forging is one of the oldest methods of producing metal articles.[1-4] It is also considered one of the best where strength, uniformity, and reliability are required. At the same time, however, it is well to remember that there is no magic about the forging process, and that unless it is carried out correctly very poor results will be obtained. Forging is to a certain extent in competition with casting as well as with machining. As will be explained later, forgings can be made with physical characteristics superior to castings. On the other hand, however, where the part is of a complicated shape and particularly where it has to be provided with hollow spaces, it can be made easily and cheaply as a casting, cored if necessary, but at times cannot be made as a forging. Where, therefore, the part is not subject to heavy stresses, or excessive vibration, it can be often preferably made as a gray-iron, malleable-iron, or steel casting. In fact, some of the modern electric-steel castings normalized or fully heat treated are not inferior in strength to the average forging. Of late the automatic screw machine has also encroached on the field of the forging. The methods of forging vary primarily with the material used and the size of the piece. Small forgings in wrought iron may be made by hand with a blacksmith fire; and many forms must be forged from a solid block, because of the loss of strength which occurs across the grain. Large, thin rings and curves of light section made of wrought iron should always be bent, but if made of steel they can be forged because steel has practically no difference in strength with or across the direction of working. The usual—practically the exclusive—method of making steel forgings is by means of a power-operated device, which may be a forging machine, a hammer, or a hydraulic press.[5]

Drop forging is a process in which dies are used, such as gang dies with edging, flatting, and rough and finish stamping impressions. The work is done under an automatic hammer. "Drop stamping" is the English name given to the process of rough forming under dummy and stamping dies of previously prepared "uses" (small billets specially prepared for the forging operation).

Terminology and Classes of Forging

Essentially, in the process of forging a change of shape of hot metal is produced under the action of great forces applied. These forces may be applied by a hand-wielded hammer as in blacksmithing or by various types of power-operated machinery, which latter may be roughly divided into two classes, hammers and presses. The distinction between the two is that in the former

the power is applied suddenly in the form of a blow or impact, and in the latter gradually and for a longer period.

This terminology is, however, largely a matter of convention. Thus, change of shape of thin pieces, cold, is referred to as pressing or stamping and not as forging. The production of impressions on metal such as in the making of coins is also referred to as stamping, although it is really a form of forging.

The change of form of a metal piece can be effected in several ways. First, it may be simply bent or twisted, either by hand hammer as in blacksmithing or by power machinery. In the latter case, as in boiler shops, it may again be done either under a hammer or between bending rolls. The piece may be so forged as to have its diameter or cross-section reduced and the length increased. This is referred to as "drawing down" or "drawing out." The process of increasing the cross-section of a piece as, for example, when a head is formed on a bolt under a hammer or press, is called "upsetting."

Forging may also be used for making a hole in a piece. This was formerly very extensively resorted to in blacksmithing work, but the introduction of drill presses made it unnecessary. Piercing under a hammer or press is still used to make comparatively large holes and, for example, in one of the methods of large seamless-tube manufacture an ingot is pierced under a hydraulic press and then rolled out into a tube. In the manufacture of hollow cylinders the billet or ingot is first pierced and then forged on a mandrel, the latter being a piece of steel introduced into the interior of the forging and of a diameter equal to the final diameter of the forged piece. The action of forging is here chiefly limited to a reduction of wall thickness and a corresponding elongation of the piece. There is obviously a certain relation between the length and diameter of the mandrel and the wall thickness of the piece. Rings may also be forged on a tapered mandrel, the diameter of the ring becoming enlarged as the piece is forced further and further over the mandrel.

A novel method of manufacturing very large ring forgings is described by W. L. Blankenship.[6] In this case the ingot is forged down and shaped into a large-loop eyebar with the ends considerably heavier than the rest. The eyebar is next split and the body of the bar slotted on a planing machine. Next a chisel-shaped drift is forced into the apex of the holes and the slot expanded from, say, the original width of 1 in. to 6 in. In this way, a piece is obtained which looks somewhat like a huge chain link, and this is next forced into the shape of a ring by the use of a convex tool or roller. For details of the process the reader is referred to the original paper.

Forging may be done on either hot metal or cold metal. Practically any external shape may be given to a hot-metal mass, and pieces of enormous size have been so forged. There are, however, very clear limits as to the size of a piece that can be commercially

forged cold, and this latter process is still mainly employed in the production of such shapes as screws, rivets, bolts, and similar light articles. This is usually referred to as cold "heading," because the forging process is applied primarily to produce a head on the piece.

Hammer or Forging Press

The matter of a selection of a proper tool in forging is very simple at times, but not such an easy matter under certain other conditions. Small forgings and forgings which are made in dies are practically exclusively manufactured under a hammer. When it comes to larger forgings the situation is somewhat more complicated. Today steam hammers above ten tons are but seldom used, and the heaviest forgings are prepared under hydraulic forging presses. Apart from the matter of practical convenience the following may be considered as a good reason for preferring the press to the hammer in the making of heavy forgings. As has been stated on p. 43, steel may be considered as consisting of two kinds of material, the crystalline and the boundary, which latter is generally called amorphous. At room temperature the boundary material is much stronger than the crystalline, but the reverse is true in the case of hot steel. Furthermore, the boundary material possesses some of the properties of a viscous fluid. If work is done on hot steel slowly as under a press, deformation takes place by flow in the boundary material, the crystals being left intact because of their greater strength. If, however, the work is applied in the form of impact, deformation takes place through the crystalline material as the boundary material has no time to flow. The high-velocity impact shatters the crystal structure, and while this has not been definitely established it would appear that such a shattering of crystals does not produce especially good results in the making of heavy forgings, and preference is therefore given to pressing.

Effect of Forging on Steel

A question which still requires an answer of proved certainty is whether or not the work done by hammering is expended mostly on the surface of the piece or extends into the interior. According to Henry Hayes[2] the process of elongation in forging is one of driving friction cones or wedges into the heated metal. These friction cones have as their base the surface immediately under the hammer, and their depth varies with the intensity of the blow. The friction cone is caused by the surface of the heated metal being held securely during the blow and partly cooled. From the surface inward this effect decreases and allows the metal to flow outward so that the flow is mostly internal.

Plastic Flow of Solids

M. Tresca, who was the first to investigate scientifically the

plastic flow of solids, states that for all bodies there are two distinct periods: the period of perfect elasticity, which corresponds to variations of length proportional to the forces applied, and the period of imperfect elasticity, during which changes of dimension increase more rapidly than forces producing them. Experiments have shown that, given the pressure of fluid necessary for the respective materials, the general form of flow when the conditions are equal is the same for all materials which experience a plastic period. From Tresca's experiments it would appear that the pressures exerted on the surface of a solid body are transmitted throughout the whole interior of its mass, and tend to produce in it a flow which is propagated from particle to particle, and which necessarily develops itself in that direction in which resistance to flow is least. The pressures thus transmitted determine in a fixed order the change of form at each point. A loss of pressure takes place internally and is variable. This is due to internal molecular friction or viscosity which resists deformation. It is these considerations that determine the flow of metal under a die, piercing punch, or press.

The following considerations in this connection were presented by Cosmo John when discussing a paper read before the Iron and Steel Institute on "The Influence of Hot Deformation on the Qualities of Steel."

> Too much work cannot be put on steel provided the temperature is right, Rolling is the least efficient way of breaking up the original crystallization. forging is better, and the best would be the carrying out of the work in all directions at once. This is only possible when forging is done in enclosed dies. The finishing blows given to a drop forging to insure that the pattern is completely filled conform to the above requirements. There remains practically no work to be done in moving the steel, therefore the whole energy is utilized in breaking up the constituents and shattering the non-metallic impurities. The material, being held in an enclosed die and subjected to an enormous impact, is made more dense, and subsequent heat treatment induces these excellent shock-resisting qualities for which drop forgings have gained repute. As the falling weight is always large in relation to the volume of metal being operated upon, the blow is penetrating, and the metal is worked thoroughly; the claim that a pressing is superior cannot be justified.

The function of hot working is twofold—to bring the ingot to the dimensions desired in the completed article, and to break up the coarse structure of the casting.[7] The finer the final structure the more ductile and tough will be the steel, other things being equal. The final fine-grained structure in turn is dependent on a proper heating both as regards time and temperature to break up the ingot structure and upon a thorough working during cooling to complete this grain refinement, a working continued to a temperature which will not allow much grain growth when it is ended.

The importance of this statement lies in the following. Not only among engineers in general, but among some forgers, rules are current to the effect that the reduction of cross-section in

forging should be not less than one in six or one in four or the like. As a matter of fact, this matter of reduction is not at all as simple as it looks. There should be enough of it to put sufficient work into the metal, and a one-in-four rule is satisfactory when dealing with comparatively small forgings, say, not to exceed 8 in. in diameter or on a side. When it comes to large forgings, however, a good deal of judgment must be used, and at times it may be found that a smaller ratio of reduction will give better results than a larger one. Excessive reduction means large ingots to start with; larger ingots mean more internal troubles, and this means poorer quality of product.

Does Forging Increase the Specific Density of Steel?

Among engineers it is generally believed that forging greatly compresses or consolidates the steel. According to H. E. Doerr,[8] while such is doubtless the case with spongy or porous iron, there is little or no change in the density in the case of steel initially free from cavities. In a series of tests made by Doerr it was found that the forged specimen is with one exception the denser of each pair. The average results indicate, however, that only 0.64 per cent of the sectional area of the original ingots consists of cavities. The ratio of volume to superficial area is so great that with an ingot of the size used ($5\,^3/_4$ in. diameter, 10 in. high) it is doubtful whether the ingot can properly solidify without the formation of microscopic cavities. With large ingots, however, where the ratio of volume to superificial area is smaller than with the ingots used, the percentage of increase in specific density of the forged specimen would be reduced to a negligible value, if not wholly eliminated.

Grain Flow

The great problem in all forging, be it die forging or forging done directly under a hammer, is to secure the proper kind of a grain flow. This is well illustrated in connection with die forging by Figs. 36 and 37.[9] These are die forgings of a crankshaft produced in the same finishing die, but with different breakdown dies. Fig. 36 shows a section in which the grain flow is all that can be desired. Fig. 37 is a section of a crankshaft produced as stated above from the same finishing die, but with material so placed that the flow is improper, and a forging of low strength is obtained. The critical section is at AA, and in Fig. 37 it is the weakest part.

Cold Heading

Generally speaking, cold heading[10] is a process wherein a piece of stock, which is usually a length of wire or rod, is placed endwise between two dies that are closed together under heavy pressure, thus causing certain unconfined portions of the stock to upset

FIG. 36 PROPERLY FORGED CRANKSHAFT

FIG. 37 IMPROPERLY FORGED CRANKSHAFT

and assume the same shape as the die cavities. The commonest application of cold heading is to the manufacture of machine and wood screws, rivets, bolts, and light articles of a similar character. Iron and steel wire with a tensile strength up to about 65,000 lb. per sq. in. is the most popular material used in cold heading. (Brass, copper and similar materials are also cold headed extensively.) The process is conducted usually on automatic machines operating on either the crank or the toggle-lever principle, that in addition to cutting the stock into lengths are arranged to form the head or upset by striking the material one, two, or three blows in quick succession. Cold heading may be carried beyond three blows, depending on the amount of metal to be upset. But three blows is the present limit in working straight from the rod, and before any further upsetting is possible the partly headed pieces must be annealed. Further upsetting is called reheading and is conducted on machines that are generally similar to ordinary cold headers, except that they have a magazine feed instead of a wire feed.

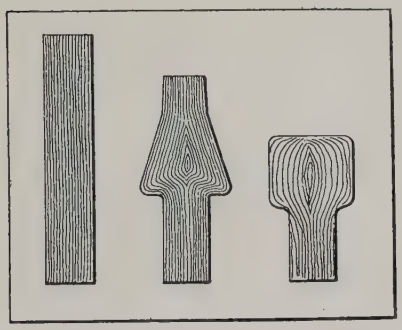

FIG. 38 SKETCHES SHOWING LINES OF FLOW IN COLD HEADING. THESE REPRESENT BLANK, FIRST CONING BLOW, AND FINISHED HEAD

Compared with other methods and their productive possibilities, cold heading is more rapid and can usually be operated at a much lower cost. From a manufacturing viewpoint it has the advantage that it almost entirely eliminates stock wastage, and provided it is properly done makes a product in every respect equal to corresponding bar products. One of the most striking examples of cold heading is to be found in the manufacture of countersunk or buttonhead screws. These can be cold headed in a modern single-blow machine at speeds varying from 100 to 150 per min. according to size.

The Society of Automotive Engineers has several specifications for steel to be used for cold heading. The carbon varies quite materially, from 0.08 per cent (soft basic open-hearth rivet wire) to as high as 0.40. Nickel-alloy steels used for cold heading seldom contain more than 3.5 per cent nickel, as steel containing more than that is too hard to be conveniently upset.

Fig. 38 shows lines of flow in cold heading. The whole success of cold heading depends upon the one point of keeping the line of flow in the material perfectly uniform. Once the line of flow is diverted, which means the core of the material is bent, no further work upon the blank will bring the flow back to its proper lines.

It is therefore a very simple matter to determine by microscopic observation of the cross-section of a cold-headed piece whether or not the work has been properly done. To be correct the material should flow from the core in sweeping outward curves. If the line of flow is interrupted the structure of the material is permanently weakened.

From another standpoint there is the question of crystallization during heading. It has become almost customary to describe a blank of which the head breaks away readily on bending as crystallized under the head. This, however, is quite an erroneous impression, inasmuch as by normalizing or annealing, toughness is once again obtained. Granted correct heat treatment of the wire, the defect is due to excessive cold work at the junction of the head and shank, and is the exact opposite to crystallization. To avoid it the amount of localized cold work must be reduced, either by alteration of the shape of the heading tool, increasing the time element of upsetting, or altering the physical properties of the steel so that it will stand up to more cold work.

Cold heading, by the way, may be combined with other processes of cold working. For example, shackle pins for automobile springs are cold headed and then sized by passing the shank through a thread-rolling machine fitted with blank dies. In England, the shackle pins are made by cold heading and sized on the shank by forcing the pins into a die fitted with a piston ejector. Valve tappets, which have a very large flat head, are also made in England for a popular light motor car by cold heading.

Machine Die Forgings

In its broadest sense, machine forging is the working of metals, either hot or cold, by means of a machine which causes the metal to flow into various shapes. This is done by pressing the metal between the dies or under a die.

Only occasionally is it possible to form and finish a forging in a single die recess. Ordinarily four die impressions are required: namely, the fuller; the breakdown, edge, or side cut, which often takes the form of a bending impression; the roughing impression; and the finishing impression. To these may be added the cut-off, if the work is to be cold trimmed. There is also the universal forging machine designed especially for forming such forgings as require squeezing, punching, or trimming operations either before or after upsetting. This often makes it possible to complete large upsets and difficult-shaped forgings in a single handling of the work without reheating.

Forging machines of the continuous-motion heading type are used principally for making rivets, track bolts, and similar products. These machines may be fed by hand or by an automatic feeding mechanism. In the former type stock is heated to a length of 4 or 5 ft. In an automatically fed machine, bars, say, 30

ft. long are heated in a long furnace set up close to the front of the machine and a feeding mechanism of the roll type draws the heated bar from the furnace and feeds it to the machine automatically after the operator starts the bar into the feeding rolls.

It is only necessary to enlarge or otherwise work the stock in order to make it fill the roughing and finishing impressions, and this is accomplished in the fuller impression. The stock is drawn out in this step in much the same manner as the blacksmith draws out stock on the anvil or under the spring hammer. Following this step, the work is placed in the breakdown or bending impression, where it is brought more nearly to the shape and size required to fit the roughing impression. The breakdown is preferably located on the right-hand side of the die, in order to make it easy for the workman to swing the bar. In some exceptional cases the roughing impression may be omitted and the work transferred direct to the finishing impression from the breakdown. However, the life of the die is materially reduced by the omission of the roughing impression. In the case of large forgings, the finishing impression is in a separate set of dies placed in a hammer near at hand to which the work may be readily transferred. Nothing is said here about the design of the dies themselves, which is a job requiring very considerable knowledge of the operation and practical experience.[11]

Forging by the Upsetting Process

This is particularly applied in such work as the manufacture of ball bearings where forging is employed to make rings from which the cups and cones are machined. The steel generally used for bearing races is S.A.E. 52100, having the following analysis: Carbon, 0.90 to 1.10; manganese, 0.20 to 0.50; chromium, 1.20 to 1.50; and phosphorus and sulphur, each not in excess of 0.03. For ball-bearing races of the smaller sizes the material is formed into rings from bar stock, while for very large sizes the ring is hammered out on a mandrel under a steam hammer. The intermediate sizes are made by upsetting.

The temperature at which the stock is forged is about 2000 deg. fahr., and this temperature must be very closely maintained both in order to produce good metal and to make a good-looking forging. If the bar is upset at too low a temperature it also shortens the life of the machine and the tools, because of the extra pressure required, in addition to rupturing the metal internally.

One of the principal laws governing upset forgings is that the limiting length of bar stock that can be upset at one stroke is equal to three diameters of the bar. The forging operation improves the quality of the steel by making it denser and more homogeneous. Forged rings made by upsetting have the advantage of grain flow in the same direction at all points around the circumference, which insures a uniform race for the balls to roll upon.

In upsetting the grains are put under compression. The increase in diameter of a forging is here accomplished[12] by the upsetting action of the grains and not by a separating or opening-up action. Upsetting can be likened to the action on an imaginary box of steel balls in which the desired shape is secured by bringing the balls into the compression necessary to force them into the desired shape. Fig. 39 is from an etching of an upset of a round ball on a wrought-iron bar. There is here a thickening of all the fibers of iron and slag. The center portion shows a greatly increased thickness, and it can be clearly seen that the fibers near the very outer edge of the upset are also thicker than in the original bar.

Upset forgings may be spoiled by the so-called staggering or slight buckling of the hot bar toward one side as it is upset, which

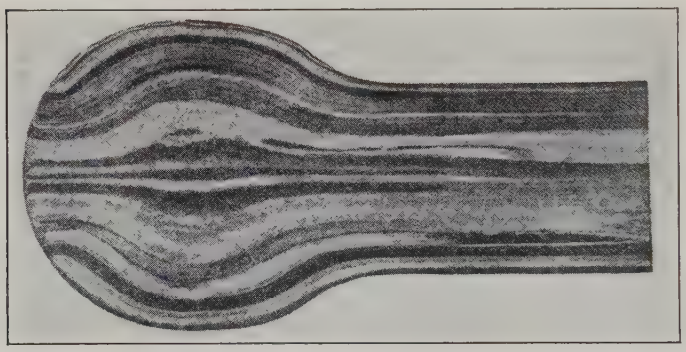

FIG. 39 ETCHING OF AN UPSET OF A ROUND BALL ON A WROUGHT-IRON BAR

results in the hole being off center and the wall of non-uniform thickness. This can be prevented by careful tool setting and the use of a bar of the right diameter.[13]

HEAVY FORGINGS

The ending of the war, and later the Washington Conference of 1921 on the Limitation of Naval Armaments, it was thought would prove disastrous to the heavy-forging industry. So many new uses, however, have developed since, that this industry is not always capable of supplying the demand for forgings. The mechanical engineer may be interested to know just what the modern forging industry can produce.

One of the most interesting recent developments is the production of large forgings in such alloy steels as chrome-nickel, chrome-nickel-vanadium, and chrome-vanadium. A notable instance of this is seen in the recent introduction of the use of chrome-nickel steel for columns of hydraulic presses, where carbon steel proved too weak and it was impossible to increase the diameters. Such columns are in successful operation today as large as 24 in.

in diameter and over 36 ft. long. A treatment giving about 115,000 lb. per sq. in. tensile strength, 85,000 lb. per sq. in. yield point, 21 per cent extension in 2 in., and 55 per cent reduction of area has answered well.

A very interesting utilization of the possibilities of chrome-nickel steel in pieces of considerable size is shown in a hydraulic intensifier built to operate under a working pressure of 40,000 lb. per sq. in., and tested to 48,600 lb., which is well beyond the 21 tons per sq. in. maximum test pressure of a modern high-power gun. Its components include the main vessel (showing a tensile strength of 143,500 lb. per sq. in., yield point of 110,000 lb. per sq. in., an extension in a 2-in. tangential bar of 15.2 per cent, and a contraction of area of 50 per cent) and subsidiary parts of various requirements, in one case showing a tensile strength of 173,000 lb. per sq. in., yield point of 137,000 lb. per sq. in., an extension in a 2-in. longitudinal bar of 15 per cent, and a contraction of area of 53.9 per cent. Results as high or higher can easily be obtained on pieces in the laboratory or the small parts for automobiles or airplanes, but such properties have not often heretofore been required in parts comparable to the size of this apparatus, the cylinder being 18 in. in outside diameter.

Chrome-nickel and chrome-vanadium steels find employment in a recently constructed 32-in. built-up container for an extrusion press. The liner is a forging of chrome-vanadium steel fully heat treated and moderately drawn back. The inner member of the container is of chrome-vanadium steel of 110,000 lb. yield point and the outer member of chrome-nickel steel of 130,000 lb. yield point, the several pieces being assembled under shrinkage similarly to a built-up gun, so that when the appliance is working under full pressure of 47,400 lb. per sq. in. no part bears over 61,000 lb. per sq. in. fiber stress.

Some remarkably large hollow-drawn forgings have been produced in connection with the manufacture of oil-cracking steels. One such forging is 46 in. outside diameter, 38 in. inside diameter, and 36 ft., $11^{3}/_{4}$ in. long. Forgings of this size are made either with the heads and covers separate and made of cast steel, or with the head integral with the body.[14]

Hollow-Bored Forgings

Experience has shown, both in England and the United States, that solid forgings of large diameter, even of soft steel, may contain internal transverse cracks cutting across the axis, and sometimes running to within a few inches of the surface. Such forgings might drop in two in the lathe when deeply turned, although apparently perfectly sound, had less metal been removed. If proper precautions are taken in casting, handling, forging, and treatment, such cracks are not produced, but as a check upon the makers the most enlightened buyers of such large forgings

are today requiring the drilling of an axial hole of a diameter sufficient to permit the introduction of a bore searcher (2 in. is about the minimum diameter) by which the interior surface of the mass can be easily viewed and its soundness verified. This should be made a regular requirement, both for the buyer's and the maker's protection. No reputable maker would wittingly send out such a defective forging, but if the buyer will not authorize boring the piece he has only the reputation of the maker as a guaranty of its soundness, unless magnetic or X-ray testing can be developed to include such sizes.

Carbon-Vanadium Forgings

Carbon-vanadium forgings are extensively used in locomotive work. When well made they are capable of rendering very good service. Their general reputation is, however, not as good as deserved, due to the fact that at the beginning of their introduction manufacturers who had no experience in making alloy steels rushed into its production, with the result that some very bad steel was made. Forging plants attempted to make carbon-vanadium forgings with the same practice they had used for the production of medium-carbon-steel forgings, which cannot be done successfully. In order to make good carbon-vanadium forgings very great care has to be exercised from the time of making the forging billet to the conclusion of the normalizing process. Non-metallic inclusions are particularly undesirable in this kind of forgings. These inclusions are found in the grain boundaries and weaken the structure by providing a starting point for a progressive fracture.[15]

The most serious difficulty in carbon-vanadium forgings are checks, and one of the causes of these is improper heating in the soaking pit. Improper rolling of billets may also produce checks as well as strains. These latter are due to an effort to make excessive reductions in rolling. If billets are heated too rapidly internal checks are produced which weaken the material very much indeed. Checks can also be produced in the normalizing process by too rapid heating. If forgings are cold when placed in the normalizing furnace and the heating is too rapid, surface expansion may be produced, causing the outside of the forging to pull away from the interior cold section. Microscopic investigation of the section which failed will usually reveal the cause of the defect. Normalizing processes on carbon-vanadium forgings consist of heating the forgings to a temperature of from 1550 to 1600 deg. fahr., maintaining this temperature a sufficient length of time to insure that the entire forging is uniformly heated, and then removing the forging from the furnace to cool in still air. The forging should be protected from drafts, rain, or snow. In the normalizing furnace it is well to support forgings several inches above the surface of the car or furnace bottom to insure complete

circulation of the hot gases for every part of the forging. In the case of forgings such as crankpins, axles, or the large heads of rods, it is advisable to have these rough-bored so that the soaking and subsequent air cooling will have the desired normalizing effect.

Forging Temperature of Steels

In the case of steel, forging is most effective at a certain temperature called the forging temperature. Forging either below or above that temperature does not give as good results as forging at just that temperature. In ordinary shop practice it is not customary to measure this temperature and it is simply estimated by the color of the metal and similar rather crude methods. Kotaro Hondo[16] suggested that the forgeability of steel at a given temperature can be adequately measured by the elongation obtained by a tensile test machine. For example, in a 0.12 per cent carbon steel the elongation at 200 to 300 deg. cent. is less than at room temperature, but at a higher temperature it increases with a rise of temperature up to 760 deg., beyond which it again decreases. When the rod is loaded at 900 deg., sectional contraction takes place not at the central portion where the temperature is maximum, but on both sides of it, which would indicate that the rod is more plastic at a temperature below 900 deg. When the temperature rises above 900 deg., the elongation rapidly increases and reaches a maximum at 1100 to 1200 deg. In a 0.3 per cent carbon steel the curve has a similar form, the minimum at 900 deg. being a little smaller. This minimum at 900 deg. diminishes from 0.3 to 0.7 per cent carbon where it almost disappears, but begins to increase again with a further increase of carbon. From this it would appear that in forging low-carbon steels every precaution should be taken against the fall of temperature to 900 deg. where the elongation is at a minimum. The cooling of carbon steels to 900 deg. is not as dangerous as in the case of low-carbon steels. A serious objection to the method used by Honda from a practical point of view is that measurement of elongation at high temperatures is not yet a commercial process. Pyrometric control is therefore the proper method to use. Where this is not used the engineer ordering forged parts has to depend on the reputation of the concern making the forgings.

Heat Treatment

All large forgings require some heat treatment to remove internal strains and to insure homogeneity. In this phase of the manufacture of extremely large forgings, each type presents its individual problems, and calls for special treatment. The proper heat treatment of a forging depends upon its size, shape, composition, the physical properties required, and its use. These factors are intimately connected.

The successful heat treatment of large forgings starts with the

handicap of the initial condition of the metal. Large masses of steel cannot be worked to as low temperatures as smaller masses, and because of this the grain structure of the forging as it leaves the press is naturally coarse and non-uniform.

The principal aim of the heat treatment is to bring about homogeneity and to refine the grain.

The treatment of large forgings usually begins with a heat several hundred degrees above the critical range, to bring about complete solution of the constituents and to eradicate the forging structure. The forgings may be cooled in the furnace or in the air, but if the cooling is accomplished outside of the furnace, the piece should be well protected from drafts of air, moisture, or any other condition which would induce non-uniformity. To refine the grain structure, a "stepped" anneal is resorted to. The initial heat is at a high temperature for the reasons given above. The second may be at a temperature slightly above the critical range, and this heat should be followed by one below the critical range. In some instances one or more additional heats above the critical range may be required to produce thorough grain refinement through the section.

In the cooling of large forgings by any method, the surface cools at a more rapid rate than the interior. This tends to produce a comparatively fine-grained structure at the surface, which becomes gradually coarser toward the center of the mass. The effect of repeated treatment, as shown by experience, is to increase the depth of the zone of finer-grained structure, and to cause a proportional improvement toward the center of mass. What cannot be accomplished with one heat on large forgings is often accomplished by several.

It is sometimes difficult to prevent warpage or distortion in large and uneven masses of metal. Heating and cooling should be as uniform as possible. The forging should be well supported in the furnace to prevent this trouble. For this reason gun forgings and long shafts are suspended vertically. On quenching, the entire piece should be dipped as rapidly as possible.

Many large forgings, both of carbon and alloy steels, are successfully given treatments, including one or more quenching operations. Turbine disks of carbon-nickel, and chromium-nickel alloy steels show superior physical properties by this method of treatment. Large high-carbon alloy-steel rolls are hardened to over 110 scleroscope hardness. Before giving large masses of metal a quench, it is best first to bore the forging to relieve the weak center line of the ingot, and thus increase the effectiveness of the quench.[17]

Crystal Growth after Forging[18]

It is sometimes assumed that forging necessarily produces a metal of fine crystallization. The following must be considered,

however, in this connection. Forging does produce to a greater or lesser extent a breaking up or distorting of the crystals, but when the forging leaves the die it may still be at a comparatively high temperature. As a matter of fact, it is easier to forge or pierce from a high temperature than from such a heat as would leave the metal in the desired state after piercing, and the average forge man may take advantage of this to facilitate his own work. The result is that when the work is laid aside to cool the crystals immediately begin to grow, and this undoes the very structure which forging was to produce. To obtain the most satisfactory results from forgings, particularly those in a single operation (where the high temperature of the metal is particularly convenient to have), it is very important to cool the metal quickly, as then crystal growth is arrested and the steel hardened at the same time.

This is particularly important in connection with pieces such as shells made from rolled billets. A rolled billet upon which a large amount of work has already been done before it reaches the forging, is placed under very favorable conditions for rapid crystal growth on being reheated for the forging operation. Tests have shown that under certain conditions after the rolling and cooling of the outside skin of a rolled billet, the interior was used at a sufficiently high temperature to admit of considerable crystal growth, and this growth was largest in that part of the bar which was the last to cool. Prolonged soaking of billets at high temperatures is to be avoided, not only on account of the coarse crystalline structure resulting, but because the carbon is likely to be diffused out of the steel through decarburization of the surface of the billet.

Where high physical properties are expected from the forging and the engineer does not care to rely upon the reputation of the maker, a photomicrograph of a section, if it is possible to get one, will tell whether or not the piece has been properly made. Normalization of a forging may help. This consists in uniformly raising the temperature of the forging to a point above the calescence range (p. 84) and cooling out under such conditions as will correct the source of weakness. The temperature should not be raised above the Ar_3 point, as then crystal growth starts and may assume an extremely rapid rate as the temperature increases. It would appear that a crystal growth obtained by raising the temperature up to the Ar_3 point is not obliterated by simple cooling, but may be eliminated by a subsequent skillful heat treating.

Hard Spots on Steel Forgings

One of the troubles encountered in forge plants consists in the appearance of so-called hard spots on forgings, which means hardening of small areas of the surface.[19] Rockwell readings taken on them usually vary between 30 and 40 and are not affected by the heat treatment which a forging is likely to receive under normal conditions. The hardness is not constant but varies,

and the readings rapidly diminish from the outside to the center of the forgings, so that the maximum value is found on the surface. Under a microscope a hard spot looks like a flake of cast iron adhering to the surface of a forging and usually having part of its carbon diffused into the metal surrounding it. Such hard spots cause a good deal of trouble when it comes to measuring a mold.

There have been a number of attempts to explain the origin of these spots. Careful investigation has shown, however, that as a rule they are not due to contamination from ingot molds. The heating in the soaking pit cannot be held responsible for it either. They do not seem to be caused by inclusion of particles of cast iron. Investigation has shown that local carburization can occur, however, in heating furnaces. Under certain conditions coke may form and adhere to the brickwork of the roof. It may then fall down and land on the surface of heating objects, as well as be covered with blanks placed in the furnace afterward. In the first case the carburization, though taking place, is slight, because due to rapid combustion of unprotected carbon the time is short and the reaction cannot take place completely. If, on the other hand, the carbonaceous material is protected in some way as by blanks placed on top of it, deep carburization has time to form and a typical hard spot is produced. It would appear, therefore, that when hard spots are found on forgings the matter should be referred back to the makers of the forgings and their special attention be called to the heating-furnace design and practice.

Ghost Lines in Large Steel Forgings

During turning operations on large steel forgings there appear at times so-called "ghost lines." When fresh they show up white and in slight relief against the steel-gray color of the mass of the turned forgings, but gradually turn light brown through oxidation. A micrographic investigation of these ghost lines[20] shows the presence of excessive streaks of dove-gray sulphide of manganese and of excessive carbon in the form of troostitic pearlite; the latter cause the "ghost" to etch dark brown, almost black. The indications are, therefore, that ghosts are due to segregation of such mobile elements as carbon, sulphur, and phosphorus.

Ghost lines appear to be little detrimental to the mechanical properties of structural steel so long as the plane of stress is at right angles to the direction of the ghost lines; in other words, when the material is in tension, torsion, or under alternating stresses. The general impression is, therefore, that ghost lines do not indicate a sign of weakness.

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[17] A. O. Schaefer, The Manufacture and Heat Treatment of Large Forgings. Transactions of the American Society for Steel Treating, vol. 7, June, 1925, pp. 714–715.
[18] C. O. Bower, Hydraulic Forging, Library Press, Ltd., London, 1921, pp. 148–149.
[19] Hard Spots on Steel Forgings, by John D. Gat. *Forging-Stamping-Heat Treating*, vol. 12, no. 1, Jan., 1926, pp. 1–7.
[20] J. O. Arnold, The Cause and Effect of "Ghost Lines" in Large Steel Forgings, Proceedings of the Institution of Mechanical Engineers, Nov., 1915, pp. 653–666.

CHAPTER VIII

CASTINGS

Castings are used in mechanical engineering on an enormous scale, and it behooves the engineer to know enough about the subject to be able to judge a casting and generally be able to design properly a part which is to be cast. At the same time it must be clearly understood that casting is still to a very large extent an art rather than a science, and that experience and skill count for as much if not for more than precise metallurgical knowledge. When, therefore, a mechanical engineer has a part which is to be either likely to be exposed to considerable stresses or which has to be made in large quantities, it may be the part of wisdom for him to consult about its design with a foundryman in whose judgment he has confidence.

Castings can be made in a number of ferrous materials. The ordinary engineering castings (i.e., not including such specialties as rolls, crushing balls, railroad track parts, etc.) are made in gray cast iron, malleable cast iron, plain carbon steel, and alloy steel. Malleable cast iron is largely used where a considerable number of parts has to be made. It is handled practically exclusively by comparatively large concerns and may be considered a special branch of founding. For general references see page 124.

Steel castings may be divided into two broad classes, namely, plain carbon steel and alloy steel. Either can be made by several processes. Plain-carbon-steel castings can be made from an open hearth, either basic or acid, from a bessemer converter, a side-blown or Tropenas converter, or a crucible or electric furnace, which again may be either basic or acid. Open-hearth furnaces used in foundries are seldom less than, say, ten tons in capacity. They are therefore not well suited to the manufacture of very small castings, but if properly handled will give excellent steel. There is no substantial difference for purposes of casting between the acid and the basic furnace, although it is generally claimed that the acid furnace is capable of producing castings with a better surface than the basic furnace; also, the reduction of area of acid steels is considerably lower than in the case of basic steels.[1] The tensile strength of the two kinds of steel, all other factors being the same, appears to be substantially equal, with a fraction in favor of acid steel. The fracture of acid-steel specimens shows a slightly coarser grain than that of the basic steels of the same chemical composition and subjected to the same treatments. The coarser grain of the acid specimens may explain their behavior with respect to reduction of area. It is also said that acid steel is more apt to develop strain cracks on cooling than does basic steel.

Electric Steel

Essentially, good steel can be made by any process, and any process can make bad steel if not properly handled. On the other hand, however, certain economic conditions have led to the adoption of the various melting processes for various purposes. There is no question about the ability of the crucible process to make steel of the very highest grade. However, it is expensive, particularly if not handled by very skilled and reliable labor, and such labor is not always available.

The electric furnace if properly handled can produce metal of the very highest grade. It is not as economical for intermittent work as, for example, a small bessemer converter, but is very well adapted for the production of light castings and for the making of special alloy steels.

In ordering castings it is important to know by which process they will be made. While essentially good castings are the same no matter which process is employed, there are nevertheless some differences. Thus the normal contraction allowance for mild steels of the converter type is $^3/_{16}$ in. to the foot. For electric-furnace steels of the double-slagged type which have been subjected to what might be called "overreducing" conditions, the common allowance is $^1/_4$ in. to the foot. On the other hand, careful measurements have indicated that single-slagged electric-furnace charges which have not been "overreduced" have a linear contraction practically identical with that of converter steel of similar composition.[2]

Bosshardt Steel Castings

A type of casting which is more or less in a class by itself is made in the so-called Bosshardt furnace, of interest because it permits controlling the carbon content down to a minimum of 0.05 per cent, while the oxygen content may be made too low to be detected by the Ledebur test.[3]

This furnace is of the open-hearth type with the usual reversible or regenerative checkerwork, and is heated by producer gas taken direct from small special gas-producing chambers built directly on the two ends of the furnace. By a slot provided in the furnace wall connected with the coal space in the producer just above the grate, flaming producer gas, mainly carbon monoxide, is passed directly into the furnace. Above this slot is another which leads from the top of the producer above the coal and so carries gas which consists mostly of compounds of carbon and hydrogen. This gas is reinforced by gas from the producer at the other end of the furnace, brought over by a cast-iron pipe above the furnace. The effect of the direct introduction of flaming carbon monoxide is to raise the flame temperature in the furnace so that far above 4000 deg. fahr. can be obtained in the furnaces. Such high temperatures are not commonly used as they would make the life

of the lining too short, but temperatures far in excess of those usual in the open-hearth furnace can be maintained to permit pouring of steel into thin-walled castings.

An article in *The Iron Age* by Sterling H. Bunnell shows some of the castings made by this process. Among them are ribbed and cored disks for water wheels and pumps consisting of unusually thin sections and complicated in design.

The hollow casting shown in another illustration, with the numerous cored openings, is about 42 in. long. There are three separate chambers in the interior, and all must be perfectly steam-tight. The pressures to which the chambers are respectively tested are 2400, 960, and 360 lb. per sq. in. The piece weighs 2100 lb. and looks to be well worth the price of $22^1/_2$ cents per lb., which of course includes a large margin of profit to the foundry.

Some of the steel castings made by the Berlin Co. operating this type of furnace in Germany are intended to replace bronze castings at a saving in weight and cost.

Casting Specifications

In certain cases more or less elaborate specifications have been adopted for castings. As an example of such a specification may be cited the recommended practice for steel castings for gears adopted by the American Gear Manufacturers Association in October, 1925.[4] Where possible such specifications should be considered with a clear understanding, however, that work to special specification in a common jobbing foundry costs more than work done by the methods regularly employed at the foundry, using metal regularly handled there. Special practice, therefore, should not be enforced on the foundry unless considered to be really necessary.

Chemical Composition

The question of sulphur content in steel castings is one requiring considerable judgment and care. Many specifications require as low a sulphur content as 0.05 and even 0.03 under the impression that higher sulphur will cause hot-shortness. Actually, however, a sulphur content under 0.08 per cent[5] may do no harm provided the molding practice is proper and enough manganese is added to counteract the effect of the sulphur. This is not really a matter which a mechanical engineer without a thorough knowledge of steel manufacture can decide for himself. Mention of it has been made here, however, merely to impress upon mechanical engineers that what would offhand appear to be an excessively high content of sulphur may under certain proper conditions be harmless. It may be asked, of course, why permit at all the highest content of sulphur in the first place merely to counteract it by manganese and not keep to a specification of low-sulphur content? The latter is unquestionably the easiest way out, but under certain

conditions a very much higher price will have to be paid for material made in accordance with a very low sulphur specification than when made under a specification permitting higher sulphur.

The mechanical engineer is apt to specify steel of low carbon content such as 0.2 per cent under the impression that castings made therefrom will be less subject to brittleness than those having a higher carbon content. This is true, but only with the important reservation that both kinds of castings are equally sound. Actually, however, the lower the carbon the more difficult it is to make steel withstand the average pouring and mold conditions. Furthermore, the lower the carbon the higher the temperature at which the steel must be cast, and the higher the temperature the more chances there are for a porous condition of the metal. Particularly in intricate castings and castings of light-section type, consistent soundness can be more easily obtained with a steel having, say, 0.5 per cent carbon than with one having 0.2 per cent.

It should be clearly understood that where the designing engineer is thoroughly convinced that the higher-carbon steel is unsuitable, he can reasonably insist on the lower-carbon specification. In doing so he must understand, however, that a superior skill in the molding and manipulation of metal is expected from the foundry and that there is more chance for the production of waste castings. The lower-carbon steel castings can be made, but only at a higher cost and by foundries having the required experience.

Structure of Steel Castings

The initial structure of a steel casting of any given composition and degree of freedom from inclusions apparently depends upon the length of time that elapses between the freezing and the passage of the solidified metal through its Ar_3 temperature. For a steel casting of given mass and design the chief variable in controlling this time interval is the time of shaking out or removal of the casting from the mold.

The iron-carbon constitutional diagram (Fig. 16) shows that in the cooling of, say, 0.25 per cent carbon steel slightly to the right of the *yx* line to the liquidus temperature, freezing begins with the formation of nearly carbon-free-iron dendritic crystals. As these iron or ferrite dendrites grow by accretion from the liquid metal, the remaining carbon-rich liquid is concentrated between the arms of each dendrite and between adjoining dendrites. Equilibrium tends to become established by the diffusion of the carbon throughout the iron. This diffusion continues during solidification and afterward during the cooling until the Ar_3 or critical temperature is reached, or until uniform distribution of the carbon throughout the iron has been attained. This diffusion is accompanied by the destruction of the dendrites. If sufficient time is not allowed for the cooling of the steel this diffusion of the carbon throughout the iron is not accomplished, and the dendritic struc-

ture is not destroyed. Fig. 3 shows how the presence of the dendrites can be easily detected by microscopic observation. Dendritic structure in steel renders it brittle. From a typical group of steel castings tested in the untreated cast conditions the following average properties were obtained.

	Cooled quickly	Cooled slowly
Tensile strength, lb. per sq. in.	84,000	80,500
Yield point, lb. per sq. in.	41,500	40,500
Reduction of area, per cent	15	26.5
Elongation, per cent	12	22
Brinell hardness	175	170
Impact, ft-lb	6	11

The annealing operation usually consists of heating the castings at a temperature of 1600–1700 deg. fahr. for several hours and then allowing them to cool in the furnace until nearly black. The effect of the initial structure as produced by the rate of cooling from molten state apparently survives the ordinary commercial annealing operation. Microscopic examination of fractured specimens has shown that the path of fracture in general passes between dendrites, indicating that the ferrite dendrites themselves are not especially brittle but that the brittleness is the property of the inter-dendritic carbon-rich filling.

Castings cooled slowly from the molten state after annealing have their pearlite, or the hard-carbon-bearing constituent, in disconnected masses, separated from each other by the soft, ductile constituent ferrite or free iron. Castings cooled rapidly by removal from the mold immediately upon solidification, after annealing, have their pearlite in connected masses or strands, or in continuous rings. Since fracture appears to traverse the pearlitic areas, a connected mass of pearlite provides a ready path for rupture, which then occurs shortly after the bar under stress begins to decrease in diameter.

When steel castings fail to meet specifications, it is usually because of low ductility rather than low tensile strength. The mechanism of failure through brittleness in low-carbon steels is not yet clear. It would appear that steel under physical test fails when the stress operating to reduce the cross-sectional area has a chance to act through a clear field of pearlite. When a piece of low-carbon steel stretches under stress the ferrite at any given point elongates and the pearlite particles around that point, being relatively brittle, are crowded together in a plane perpendicular to the axis of the piece. When this aggregation of pearlite reaches a degree such that it forms a field across the bar, failure occurs, presumably because the pearlite is unable to undergo the compression that a further decrease in the cross-section of the bar would involve. If that theory, presented in particular by Stanley A. Richardson, Assistant Professor of Metallurgy, Lewis Institute,

Chicago, is correct, the ductility of low-carbon steel would appear to be a function of the distance between its pearlite particles, and the cause of a failure could then be easily discovered by microscopic investigation. (Usually, however, only after failure to take place.)

Defects in Steel Castings

Porosity. Many cases of porosity in castings are due to improper foundry practice, such as badly vented molds or cores, the use of sand which does not permit escape of gases, excess of moisture in the mold, etc. With these the mechanical engineer has nothing to do, of course. In general, however, the following should be taken into consideration. Porosity appears to be more common in electric steel, possibly as a direct outcome of an excessively high casting temperature. It is easier to make such excessively hot metal in an electric furnace than in other kinds, and cases have been known where the first castings made from a ladle were porous, while the latter ones were solid. It is possible at times to establish definitely what the porosity was due to. If analysis shows that the silicon content was too low for safety, the blame is on the metal. Where porosity is general it is usually due to improper foundry methods. Odd cases of porosity or local porosity in a casting otherwise good may be due to faults in molding.[7]

There are certain classes of castings where it is important to look for porosity. This is apt to take place in large cylinders where the walls are excessively thin.

In connection with the matter of blowholes, the following quotation from a report by the engineer-physicist of the Interstate Commerce Commission, Dr. Jas. C. Howard, may be of interest. In this case a defective truck frame was suspected to be the cause of a train wreck. Fracture of the frame occurred, it is stated, at the inner corner of the journal-box jaw. The surface of the rupture presented two distinct phases: an earlier and progressive type of fracture for a part of the fractured surface, and the final stage at which time rupture was completed. The report says in part:

> The casting showed numerous blowholes in the inside rib. Blowholes exist in many if not in most steel castings. They are necessarily a source of weakness wherever found. At one place the blowholes represented nearly 100 per cent of the cross-section of the rib of the frame. It is not held that blowholes were primarily responsible, possibly not remotely accountable, for the fracture of this frame.
>
> This was a cored casting. The core was not set concentric with the ribs. There were variations in thickness of the ribs, ranging from a maximum of 0.58 in. to a minimum of 0.24 in. at the end fractured under the gondola car. At the opposite end, where fractured by a steam hammer, the thickness of the ribs ranged from 0.30 in. minimum to 0.64 in. maximum. This variation in thickness of the metal is correctable in the foundry by the exercise of care in setting the cores.
>
> The direct cause of the fracture of the frame is attributed to error in the

design, resulting in deficiency of metal at a vital place where working stresses attain maximum values.

There is general knowledge of the fact that severe shrinkage strains are set up in steel castings, with the possibility of cracks forming at critical places. Such a condition is referred to as a "draw" in a casting. Strains not relieved by actual separation of the metal are measurably diminished by annealing. This casting was doubtlessly annealed.[8]

Contraction Cracks. The metal in a casting contracts in two ways.[7] The first contraction takes place in steel when the metal passes from the liquid to the solid state. This does not occur in cast iron, however. The next contraction takes place, except at the critical points, as the metal cools from the freezing temperature to room temperature. If the shape of the casting and other conditions are right this contraction does not produce any harmful effects. Otherwise it leads to the creation of stresses and may result in what are known as contraction cracks.

Unless special precautions are taken, mild-steel castings, particularly if of a fragile, light-sectioned nature, are very liable to crack on cooling.

Mild steels high in sulphur are notably tender when cooling from the liquid condition. To some extent this can be counteracted by working with a fairly high manganese content. By the formation of manganese sulphide in such a manner, which exists as minute dots throughout the steel, the alternative formation of iron sulphide is prevented. Iron sulphide, having a low fusion point, exists between the iron crystals in a more or less filmy form, thus partially destroying their cohesion. After the crystals are formed and the material solidified, such sulphide can still remain fluid, causing the material to be excessively weak at a red heat, and to offer little resistance to the strains to which it is subjected during cooling and contraction.

Here again analysis points out the cause, which should never exist in basic electric steel. One of the most valuable properties of the basic electric furnace is its ability to produce with ease very low-sulphur material.

Badly made steel, tapped in a "rising" condition,* is sometimes corrected and made apparently sound by overdoses of aluminum. This is very bad practice, and such material is also very liable to crack. This is no doubt due to the inclusion of quantities of non-metallic material, such as alumina.

Given a good steel, and normally careful methods of molding

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* By steel in a rising condition is meant steel which increases in volume in the mold, and hence "rises" somewhat like dough. The reason is the same in both cases, evolution of gases. In the case of dough the gas is mainly carbon dioxide, and is due to the fermentation produced by the yeast. In "rising steel" it is mainly carbon monoxide, and its evolution is due to the deoxidation of the steel by the carbon present in the steel. Cp. Carl Pierce, Making Rimmed Steel, paper (1926) before the American Institute of Mining and Metallurgical Engineers.

to prevent cracks, faulty designing is responsible for more trouble with cracked castings than any other cause. Designs are often submitted to the steel founder which have been evolved quite obviously with only one object in view, namely, to fit into the place desired by the designer. Indiscriminate variation of section, the existence of large bosses demanded solid on otherwise thin-sectioned castings, are often a perfect bugbear to the steel foundryman, and his failure to give satisfaction is no doubt attributed to his ignorance. While intelligence properly applied when making the molds will assist materially in preventing such cracks, no skill of the molder will reverse the natural laws governing the solidification and cooling of steel. Its comparatively high degree of contraction, its high melting point, and weakness at high temperatures are all definite facts over which the founder can exert no control. He can only take all possible precautions to prevent their causing an excessive degree of trouble. Granting the engineering demand as regards general design, the designer of a cast part should as far as possible bear in mind the following points: (*a*) section of metal should be as even as practicable; (*b*) sharp changes of section and sharp corners should be avoided wherever possible; and (*c*) the minimum number of heavy bosses, which latter should be cored out if in an inaccessible position for feeding, a state of affairs which often exists.[7]

Shrinkage Cavities in Castings. When shrinkage cavities occur in castings in ordinary practice, i.e., excepting castings of very unusual dimensions or shape, the fault may be due either to improper design or improper foundry practice.[9] The matter of design is discussed elsewhere. When the design is right, a factor which affects the reduction of castings with sections free from internal strains is the shape of the riser or feeding head used. This is the foundryman's term for the lumps of extra metal added to certain parts of the casting on its uppermost side when the mold is in position for pouring steel into it. Later on this excess metal is removed from the casting, but it forms a reservoir of liquid metal upon which the sections of the casting draw while shrinkage and solidification of the metal are taking place. There may be several heads on a single casting, the number being governed by the design of the casting and the metals used.

Thick and Thin Sections in Castings

If there is one thing that an engineer designing a cast part which will be subject to strains must realize, it is the importance of understanding that under ordinary casting conditions the strength of a thin section is vastly different from that of a thick section. From this point of view the illustrations in Figs. 40 to 42, taken from an article by F. C. Edwards, are of interest.[10] The first two were taken from specimens of cast-iron bars 3.3 per cent silicon cast in green sand under similar molding conditions and

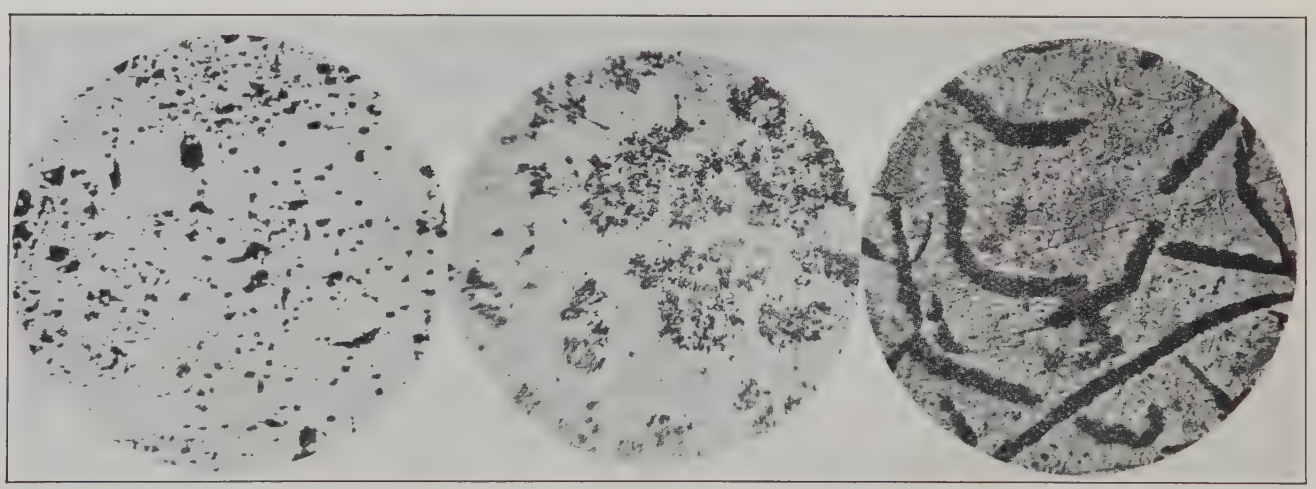

FIG. 40 FROM 2-IN. × 1/8-IN. TRANSVERSE SECTION; PROPORTIONAL BREAKING STRESS, 20 TONS PER SQ. IN.

FIG. 41 FROM SAME LADLE AS METAL SHOWN IN FIG. 40, 2-IN. × 1/2-IN. TRANSVERSE SECTION; PROPORTIONAL BREAKING STRESS, 13 TONS PER SQ. IN.

FIG. 42 FROM 4-IN. SECTION OF BEDPLATE WHICH FAILED UNDER TEST

(Originally × 100. Reduced by about × 0.85 on reproduction.)

poured from the same ladle. While, however, Fig. 40 refers to a member having a transverse section of 2 in. $\times$ $^1/_8$ in., that of Fig. 41 was 2 in. $\times$ $^1/_2$ in. Of three tensile tests on each size of bar the average breaking load for bar Fig. 40 was 5 tons, equivalent to 20 tons per sq. in. The average breaking load for bar No. 20 was 13 tons per sq. in. To this great difference in tensile strength there is a corresponding difference in the size and shape of the graphite carbon shown as black spots in the two figures. In Fig. 40 the graphite is "nodular" in shape and is fairly evenly scattered. Such a formation is found to imply strength. The graphite in Fig. 41 is that a coarser nature, while the graphite in Fig. 42 is of a heavy flaky formation. These flakes of graphite may be said to have no strength at all, and as a matter of fact Fig. 42 was taken from a 4-in. section of a large bedplate which failed while under test.

Uniform Cooling in Casting

An interesting example of the trouble that may arise from lack of uniform cooling in casting is given by F. C. Edwards,[11] Figs. 43 and 44, which represent an end frame weighing about 1900 lb. This casting was placed in the foundry yard the day after it was cast. The following morning it was found fractured right across the middle, as shown as *A*. A space of $^3/_4$ in. separated the two portions. Between the ribs much rainwater had collected; for the casting had been subjected to a deluge, which had visited the district the previous evening. A close examination of the fracture, and certain inquiries, left no doubt that the casting was sound when placed outside.

At that part of the casting where fracture occurred the metal averaged 1 in. in thickness. The overall width of the casting was 24 in. The sides were each 7 in. deep—i.e., a total area of 36 in. of metal fractured. The casting was of "semi-steel" the test bars of which regularly average 16 tons per sq. in. tensile. The metal at the fracture was sound. It should also be noted that the temperature of the part fractured was not high enough to reduce the strength of the metal to any appreciable extent. Now, if a breaking load of but 10 tons per sq. in. tensile is assumed for such a fracture, we find that to pull this casting apart—as it manifestly had been pulled during the process of cooling—we should require the enormous total of 360 tons.

Such an example conveys a very useful lesson, both to designer and foundryman. It is, of course, an extreme case, but in this lies its special value. For it exemplifies, on a large scale, the operation of forces undoubtedly present during cooling in all castings—large or small—and indicates, pretty conclusively, their probable sources.

In this case, these appear to be of dual origin: (1) Unevenness of metal section; and (2) accelerated cooling. It will be seen from Fig. 43 that the ends of the casting are of a much heavier section than

that of the part fractured. Particularly is this the case with the bearing blocks *B*. Here, the metal in the body of the block is 6 in. × 3 in.; and where the blocks join the body of the frame the section is still greater. Moreover, the disparity is further aggravated by end projecting pockets cast on the back of the frame, shown at *C*, Fig. 44. This extreme difference of metal section, therefore, would

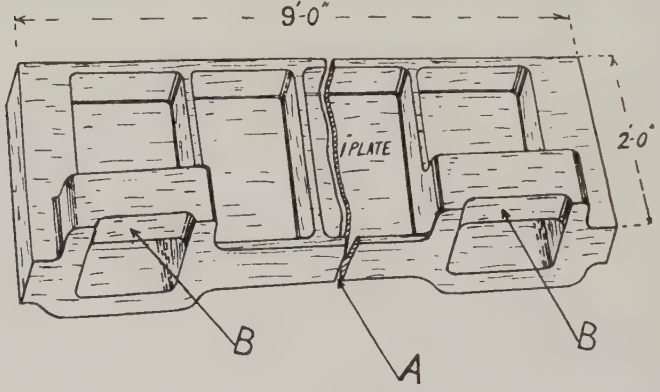

FIG. 43 AN END-FRAME CASTING (WEIGHT 1904 LB.) SHOWING FRACTURE AT THINNER SECTION AT *A*, AND HEAVY END MASSES AT *B*

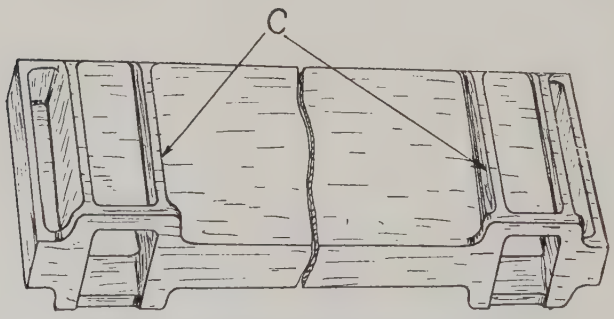

FIG. 44 REVERSE SIDE OF CASTING SHOWN IN FIG. 43, SHOWING PROJECTION POCKET *C*

inevitably militate against uniformity of cooling, and this in spite of the fact that castings are uncovered at the ends soon after being cast.

Such a casting would not be quite cold when placed outside the day after it was cast. Indeed, it may safely be assumed that the interior of the heavier sections would retain heat long after its exterior had apparently cooled down. This residual heat would represent potential shrinkage. And a further drop in temperature would therefore be accomplished by a further shrinkage of the

casting. This shrinkage, it should particularly be noted, would be almost entirely *local*—not *general*. Each end of the casting would constitute a "shrinkage field" in itself. Moreover, in each shrinkage field, independent forces would operate towards its own center so long as shrinkage continued.

Heat Treatment of Steel Castings

Ingotism or excessively large grain structure of steel can be broken up and refined by heating the material considerably above the critical range, allowing to cool, then reheating to a lower temperature and holding long enough at that temperature to insure the penetration of the heat to the center (soaking). The material is then allowed to cool to atmospheric temperature either in the furnace or in the air, depending upon the properties desired in the finished product.[12]

When steel has not been thoroughly "killed" by the deoxidizers, gases which have been contained in the liquid metal are given off while solidifying, since the solubility of these gases in the steel becomes less as the temperature approaches the freezing point of the metal. These gases, trying to escape through the pasty metal, which is part liquid and part solid, form cavities called "blowholes," which give the castings a honeycombed appearance, and cut down the effective area for resistance to stress. Also, the gases remaining in solution are believed to have a depressing action on the critical point of the steel at these locations and cause exaggerated crystal growth. The proper elimination of this condition lies in the working of the liquid charge before tapping, so as to leave always sufficient residual manganese to unite with the dissolved oxides and proper "killing" in the ladle. Some plants add high-silicon pig iron just before tapping in order to conserve the manganese content of the metal and claim to get a better scavenging action from the final recarburizers.

When this porous condition does exist in the castings, the heat treater must restore the physical requirements to the material, which is again accomplished by a double treatment, first refining the normal part of the casting and then the oxidized portion. Another form of gas pockets exists in steel castings, which results from pouring the metal into molds, which are not sufficiently dry and not properly vented. The hot metal reacts upon the gas-producing constituents of the facing sand and cores in the mold, giving off gases which cannot properly escape through the dense sand, and the result is a porous section in the casting at this point. Since the entrapped gases in cases of this kind nearly always contain a considerable amount of air, the surfaces of these cavities many times present an oxidized appearance, and microscopic examination reveals the fact, that, in many cases, the surrounding metal has been decarburized to a considerable degree. This decarburization leaves an excess of ductile ferrite at these points, which reduces the strength

of the section. The proper elimination of this condition is to prepare the molds from properly tempered sand and to be sure that the backing sand is more permeable than the facing sand in order that the gases may escape freely. When it is necessary to heat treat a decarburized section a treatment which will largely develop a sorbitic structure which gives notch toughness to the surrounding inaltered material is best, so that as the ferrite yields under stress, the strain will be taken up by the stronger material.

Reference was made above to "killing" of steel. This means introducing into the molten metal some material that takes care of the gases. These gases may be oxygen or carbon monoxide. The real material that has to be eliminated is oxygen. This may be present in the form of iron oxide which under a certain temperature condition is attacked by the carbon present in the steel producing

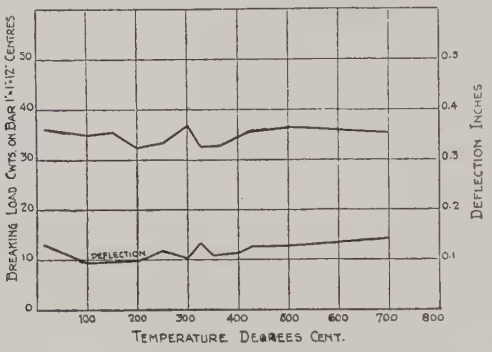

Fig. 45 Transverse Strength of Semi-Steel at High Temperatures After Annealing

carbon monoxide. There are two ways of handling this situation, one is by introducing such deoxidizers as silicon usually in the form of ferrosilicon, or manganese as ferromanganese, into the metal bath—at times into the ladle, particularly with manganese. The other way is by introducing very powerful deoxidizers like aluminum into the ladle. This latter process is apt to result in inclusions of oxide of aluminum throughout the metal, such inclusions materially weakening the ability of the metal to resist shocks. It is because of these latter circumstances that railway specifications prohibit deoxidation by aluminum in the manufacture of rails.

Where a cast part is not exposed to shocks or high stresses, deoxidation by aluminum in the ladle would appear to be permissible.

Heat Treatment of Semi-Steel

According to Professor Campion,[13] semi-steel is stronger than ordinary cast iron and is therefore better suited for use in internal-combustion-engine cylinders, liners, etc. There is a marked loss of

strength at temperatures above 500 deg. cent., but for equal time of heating the rate of reduction in strength is less than with cast iron. Semi-steel castings may therefore be annealed and yet retain the desired strength.

The effect of the transverse strength of the same semi-steel is shown in Fig. 45. The material undergoes very little change when annealed at temperatures up to 700 deg. cent., but between 250 and 350 deg. cent. it behaves erratically as regards both breaking load and flexibility. There appears to be some change which occurs in this region in all cast-iron materials, as transverse and impact tests, as well as tensile strength, while hot show discontinuity. The reason for such erratic behavior has not yet been found.

Gray-Iron Castings

While the metallurgy of steel castings is rapidly developing, that of gray-iron castings has never received sufficient attention and is apparently more or less at a standstill. This is due probably largely to the fact that gray-iron castings are used where great stresses are not expected to be encountered. The questions of strength, solidity, absence of internal cavities, etc., are therefore of much less importance in the case of gray-iron castings than in the case of steel castings. The surface appearance is probably the most important element in the manufacture of gray-iron castings, and this is a matter which can be judged by any one without special metallurgical knowledge. Nevertheless there are certain features which may be of interest to mechanical engineers and these will be briefly discussed here.

Treatment of Castings While Cooling

Castings which have been molded or poured correctly are often found to be warped and distorted on their removal from the sand.[14] This may be due either to improper design or to improper treatment of the casting before its removal from the sand. If a heavy part of the casting immediately adjoins a light part, the latter will solidify first and the heavy portion, cooling later, will shrink and tend to draw away from the lighter portion. If the casting does not rupture in this operation, strains may be set up which will warp the casting out of shape and thus render it worthless. This contingency may often be avoided by exposing the heavier part of the casting to the air, thus making it cool more rapidly while the cooling of the lighter portion is retarded, the entire casting thus becoming solid at about the same time. Shrinkage strains are thereby avoided and the casting is removed from the sand true to pattern. The cooling of the lighter parts is retarded often by covering them deeply with sand at the same time that the heavier parts are exposed to the air.

Oftentimes from the shape of the pattern can be predicted the method in which the casting will cool and the extent to which it

will be distorted if allowed to cool normally. This distortion can be avoided and the effects of unequal cooling counteracted by distorting the pattern in the opposite direction an amount equal to that distortion it would assume in normal cooling. Thus, in casting columns, the pattern is made with the ends relatively lower than the middle portion. The mold is made with the middle of the column higher than the ends which cool last. They are thus thrown up as the casting cools and if the right amount of camber has been given to the pattern the column will be perfectly straight when cold.

Where castings are made with heavy, rigid cores in them they may be ruptured by shrinking on these cores. Thus, jacketed cylinders having light walls and heavy barrels must have the cores removed promptly to prevent the barrel cracking away from the jacket. Cored cylinders frequently have internal strains set up in them by shrinking on the cores, and when the first roughing cut is made on them in the machine shop these strains are relieved and warp the casting, which as a result must be annealed.

After the casting has been removed from the sand, care must be exercised in its treatment until it has cooled down to room temperature. A large casting which may be exposed to a chilling draft on one side, such as might come from a door communicating with outdoors in the winter time, would cool more rapidly on that side than on the other and thus crack just as surely as it would in the mold had no provision been made for crushing the cores. Printing-press cylinders exposed to unequal temperatures on opposite sides are especially liable to warping.

The composition of the iron of which the casting is made also has an influence on its treatment after pouring. Light castings of machine parts are usually removed from the sand immediately after the mold is poured. These castings are high in silicon and low in sulphur, manganese, and combined carbon. A coating of sand frequently adheres to such castings in proportion to the thickness, protecting them from the air. However, if air does come in contact with the casting, the high silicon and the high graphitic carbon content prevent the formation of a hard scale. On the other hand, if the sulphur and manganese contents are high the reverse will be true and a hard scale will form on the castings if the air is permitted to strike them before they have cooled to room temperature. It is therefore advisable to leave them in the sand until they are cold, especially if they are to be machined later. Should it be necessary for any reason whatever to remove them from the sand promptly, they should be poured with iron of a silicon content about twenty points higher than ordinarily.

The thinner the wall of the casting to be machined the greater is the danger of removing it from the sand too quickly and of forming on the surface of it a hard scale. When uncovering such castings, to equalize the cooling a small amount of sand should be allowed

to remain on surfaces which are to be machined. This will prevent direct contact with the air and thus avoid scale and yet will permit the rapid escape of heat.

Castings which are found to be crooked on removal from the sand may be straightened by heating them to a red heat and then weighting them so that the casting will be bent in the opposite direction. Lathe beds and similar castings may be treated in this manner, the ends being placed on solid bearings, the casting arching upward and being heated at the center until it is red hot, after which it is weighted and allowed to cool. Many times castings may be straightened by peening on the hollow side, thus closing the grain of the iron and forcing the ends down.

The Effect of Chill

The composition and structure of cast iron is materially affected by the rate of cooling. Extremely rapid cooling can be produced by what is known as a chill, this being effected by so arranging the mold that heat will be rapidly carried off—for example, placing metal surfaces in contact with the incoming iron. Molten iron contains in solution certain impurities and its ability to hold them in solution depends on its temperature, the same as the ability of water to hold sugar in solution varies with the temperature of the liquid. As the iron cools it loses some of its power to hold the impurities. Rapid cooling of iron produces a rejection of impurities from the outer surface toward the core, and therefore makes the metal near the surface more uniform in composition and more apt to be mechanically strong. True, a corresponding weakening of the core is produced, but this is usually not essential. Tests carried out on chilled cores and also on a section cut from a block of gray iron frozen in the ladle confirm the statement that the impurities, particularly phosphorus, tend to be driven toward the center of the casting as a result of chilling.

Internal Chill

At times white patches are found in gray-iron castings. In a paper before the Institute of British Foundrymen, H. Beeny[15] stated that as a matter of fact so far as he knew there was no satisfactory explanation extant, though there were several theories or reasons put forward. One was the segregation of sulphur at certain points within the mass of metal. It was well known, he said, that sulphur had a whitening effect upon metal, and was supposed to prevent decomposition of the pearlitic carbide. So whenever there was this segregation of sulphur, white patches would likely be found provided the balance of the other constituents of the metal was such as to give a metal sensitive to the influence of sulphur. Then there was the point of pressure. Graphite occupied more space than carbon existing as carbide; if there was a strong outer casing to the metal, graphitization proceeded up to the point when the very

considerable pressure in the interior prevented its further information.

This internal chilling is at times very persistent and is not readily removed by an annealing treatment, particularly where the sulphur content in the iron is high.

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